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# 16-inch gun-launched anti-satellite weapon

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# NAVAL POSTGRADUATE SCHOOL
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# THESIS

16-INCH GUN-LAUNCHED ANTI-SATELLITE WEAPON

by

Joseph John Natale

June 1982

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# 16-Inch Gun-Launched Anti-Satellite Weapon

by

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Submitted in partial fulfillment of the
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# I. INTRODUCTION

There are four events which suggest that a feasibility study should be made of the 16-inch naval gun as an anti-satellite, ASAT vehicle launcher. The first event is the paper by A. M. Valenti, Sannu Molder and G. R. Salter [Ref. 1] which indicates that a gun-launched supersonic-combustion ramjet, scramjet, is capable of 50-g acceleration and Mach 15 velocity. There is also the paper by C. H. Murphy, G. V. Bull and E. D. Boyer [Ref. 2] which indicates that a gun-launched rocket is capable of placing a payload in a highly elliptical 19,000 nm by 500 nm orbit. The second event is the U.S. Air Force development of a rocket-propelled, miniature ASAT weapon to be launched from the F-15 aircraft [Ref. 3]. The third event is the recommissiong of at least one Iowa class Battleship, consequently bringing nine 16-inch guns into service. The fourth event is the proliferation of long range anti-ship cruise missiles. To survive, a Naval Task Group must deny the enemy over-the-horizon targeting information provided by Ocean Surveillance Satellites [Ref. 4].

The USAF ASAT system involves the placement of a Miniature Vehicle, MV, which is a highly sophisticated homing weapon, in a sub-orbital acquisition window [Ref. 3]. The problem is, can a 16-inch, gun-launched vehicle place this or a similar MV ASAT weapon in the required sub-orbital acquisition window?

## II. BACKGROUND AND DEVELOPMENT

### A. THE MINIATURE ANTI-SATELLITE VEHICLE

Aviation Week [Ref. 3] describes the USAF ASAT as:

> Miniature vehicle anti-satellite weapon under development by the U.S. AIR FORCE SPACE DIV and Vought would utilize long wave infrared homing combined with laser-gyro stabilization and an extensive lateral maneuvering capability to collide with and destroy a hostile Soviet spacecraft.[p. 243]

The Air Force system actually uses the F-15 aircraft as a first stage; a Boeing short-range attack missile (SRAM) and a Vought Altair are used as second and third stage vehicles. The F-15 flies to a predetermined position and altitude and launches the SRAM-Altair-MV vehicle. The SRAM provides the majority of accelration. The second stage Altair spins the MV to 20 revolutions a second. After the target has been acquired by the MV, the MV is released by the Altair. The MV is described as being approximately 12 x 13 inches in size. [Ref. 3]

### B. THE 16-INCH, 50-CALIBER NAVAL GUN

The 16-inch, 50-caliber naval gun, like the nine aboard the USS NEW JERSEY, has a 16-inch diameter bore. The barrel is approximately 66 feet long. The maximum gun elevation is 45 degrees. Standard projectiles weigh about 2700 pounds with a typical muzzle velocity of 2800 feet per second [Ref. 5]. The values above vary with charge and projectile weight.

Performance of the 16-inch gun when projectiles with smaller mass are used can be predicted. Assuming a frictionless barrel, which should be nearly feasible with silicon or teflon coated projectiles,

$$U = \left( \frac{P}{m} 2AL \right)^{1/2} \tag{1}$$

P = average pressure on the base of the projectile
m = mass of the projectile
A = base area of projectile
L = length of barrel
U = muzzle velocity

Using $P = 1.58562 \times 10^8$ N/m$^2$ or 23,000 lbf/in$^2$, $A = 0.1297$ m$^2$, and $L = 20.32$ m, the Mach number as a function of projectile mass is:

$$M = \left(\frac{8.3578 \times 10^8}{m}\right)^{1/2} \times \frac{1}{340.3} \tag{2}$$

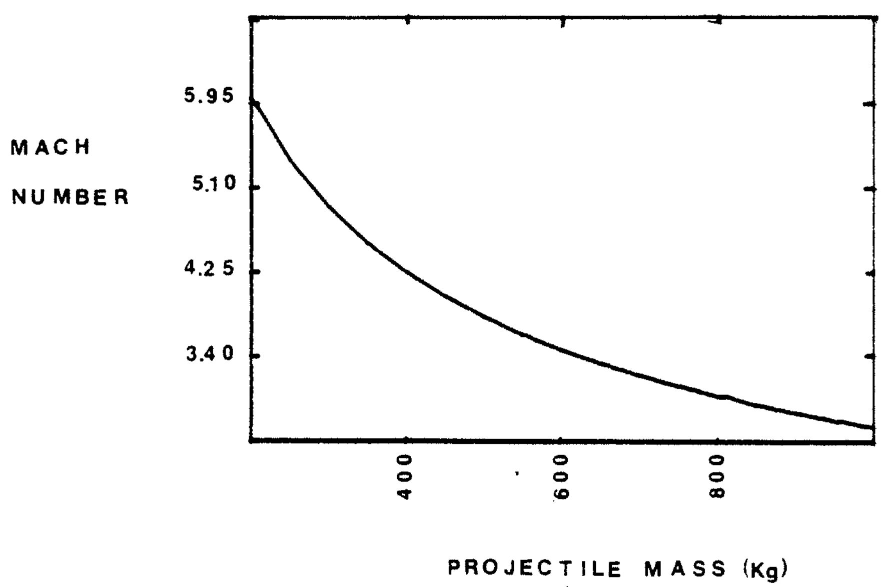


Fig. 1: MUZZLE MACH NUMBER VS. PROJECTILE MASS

The results of Figure 1 are substantiated by D. Monetta [Ref. 6].

## C. 16-INCH GUN ASAT WEAPON

### 1. Target Altitudes

Ocean reconnaissance and targeting satellites are presumedly the primary targets for a Naval ASAT system [Ref. 3]. Their ability to locate and identify ships simplifies the Soviet over-the-horizon targeting problem. The Soviet RORSAT, Radar Ocean Reconnaissance Satellite, orbits at an altitude between 250 Km and 260 Km. The Soviet EORSAT, Electronic Intelligence Ocean Reconnaissance Satellite, orbits at an altitude between 430 Km and 440 Km [Ref. 4]. The altitude achieved by the gun-launched ASAT should be sufficient to intercept these satellites.

### 2. Mission Profile

Figure 2 depicts a possible 16-inch gun-launched ASAT mission profile. The 16-inch gun performs the function of a first stage booster, accelerating the boost vehicle, which includes the miniature ASAT vehicle, MV, to a velocity between Mach 3 and Mach 5. The boost vehicle should accelerate to a velocity between Mach 7 and Mach 9 and increase the flight path angle as measured from the horizontal to between 50 and 85 degrees. The MV and support equipment will detach from the boost vehicle at 150 Km. As the MV approaches the apogee, target acquisition occurs and lateral guidance corrections are made as necessary to achieve an intercept [Ref. 3].

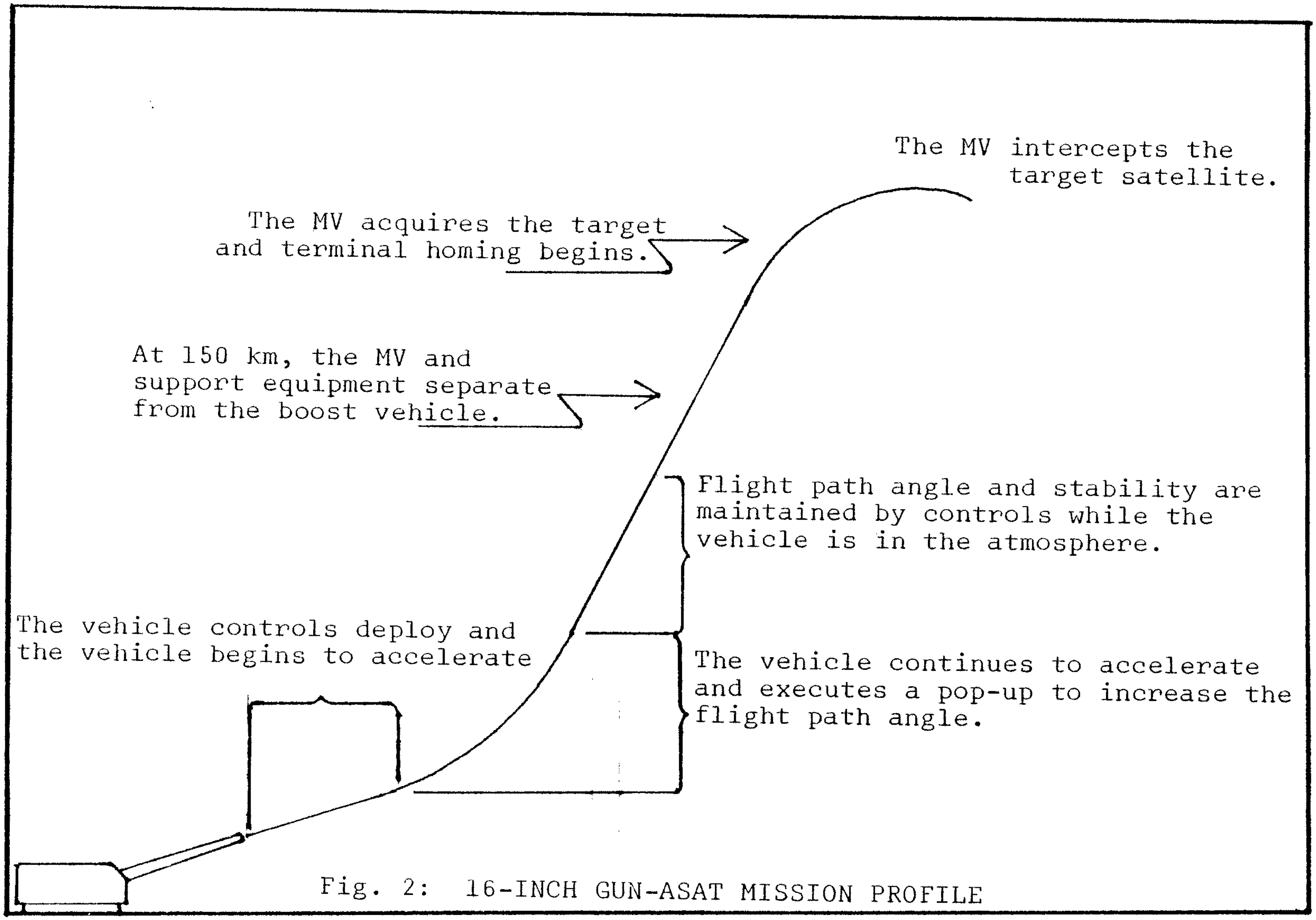


Fig. 2: 16-INCH GUN-ASAT MISSION PROFILE

### 3. Physical Characteristics

The boost vehicle may have a diameter as large as 16.5 inches if the gun is fitted with a smooth bore liner. A smooth bore in one of the nine 16-inch barrels on the Iowa class Battleship would not significantly degrade the ship's firepower. A smooth bore gun may also find additional applications with gun launched guided projectiles.

The vehicle may be sub-caliber if saboted; however, a sub-caliber vehicle with a diameter less than 14 inches will not accommodate the existing MV. The length of the vehicle is governed by the amount of handling room in the gun turret, by the barrel length and by the ability of the vehicle structure to withstand loading due to acceleration in the gun. The standard 16-inch projectile is approximately 80 inches long. Assuming the boost vehicle can be sectioned and assembled while being loaded into the gun, it could reasonably be 192 inches long [Ref. 2]. Acceleration within the barrel will range from 2600-g's to 7200-g's. The duration of this peak loading is from 0.04 to 0.02 seconds. If 120% yield stress is used as a working stress, it is reasonable to predict that 50 - 75% of the vehicle weight will be required for the structure [Ref. 1].

## III. BOOST VEHICLE

The compatability of the boost vehicle with the 16-inch gun-launcher dictates many of the vehicle characteristics. Primarily, the vehicle is volume limited. The vehicle mass is also a key factor. The vehicle mass, as in any missile, is a function of payload, fuel, structure and controls; however, in this specialized application, mass also affects the muzzle velocity, $V_0$. Assuming vehicle with a mass of 350 Kg is used, the $V_0$ obtainable is 1360 m/sec, which is Mach 4.5. For the EORSAT mission, the intercept trajectory requires the vehicle to be at a velocity of 2618 m/sec, V, at 10 Km altitude. To achieve the required velocity, the vehicle must be capable of 7.9-g's of acceleration, A.

$$\frac{A}{g_0} = \frac{(V-V_0)^2}{2g_0h} \qquad (3)$$

Muzzle velocity may be increased, thereby reducing the acceleration requirements. However, an increase in $V_0$ is at the expense of fuel and/or payload. The required strength and consequently the mass of the vehicle case can only increase with increased $V_0$.

The majority of the air breathing engines are not applicable as a result of their inherent performance limitations. This includes the subsonic combustion ramjet, due to a low

acceleration limit. The supersonic combustion ramjet, scramjet, is, however, theoretically capable of 50-g acceleration [Ref. 1].

Solid or liquid fuel rockets of single-or multi-stage design are a second potential souce of propulsion.

## A. SCRAMJET

### 1. Scramjet Background

Considerable research was focused on scramjets during the late 60's and early 70's. This included the testing of a Mach 7.0 gun-launched scramjet in 1975 [Ref. 7]. The detailed analysis required to develop a completely accurate model of a scarmjet is beyond the scope of this thesis. Therefore, various assumptions are made to simplify the scramjet model. The goal is to first determine system feasibility and to second identify areas requiring additional study.

### 2. Scramjet Model

The first assumption in this model is that $\gamma$, the ratio of the heat capacities, is constant and equal to 1.4 throughout the scramjet. Admittedly this is an erroneous assumption as the temperatures and pressures involved exceed the realm of ideal gas. Never-the-less the straight-forward evaluation allowed by the use of equations for ideal gas provides an optimistic, yet relevant, performance base-line for overall scramjet boosted ASAT system evaluation.

The scramjet was modeled in two sections, inlet and combustor. The nozzle is assumbed to be capable of expanding the flow to the ambient pressure, $P_0$, at all altitudes. The inlet is assumed to have variable geometry which will maintain a constant ratio of $M_3/M_0$ for all values of $M_0$. This performance characteristic is assumed to be achievable and is derived to maximize the thrust [Ref. 8]. The design of this inlet may, in fact, not be feasible and is an area requiring additional study.

a. Combustor

As shown in Figure 3, air enters the combustor at point 3 at some Mach number, $M_3$. $M_3$ is a function of the free stream Mach number, $M_0$, the kinetic energy efficiency of the diffuser, $\eta_d$, and some stagnation pressure, $P_{T3}$. $P_{T3}$ is a function of the ratio of $P_{T3}/P_{T0}$, $\pi_d$. If $P_{T3}/P_{T0} = \pi_d$, $P_{T5}/P_{T3} = \pi_b$ and $P_{T6}/P_{T5} = \pi_n$ and complete expansion is assumed in the nozzle, then

$$\frac{P_{T6}}{P_{T0}} = \pi_n \times \pi_b \times \pi_d \qquad (4)$$

Static and stagnation pressures at entrance and exit are related by

$$P_6 = P_0 = \frac{P_{T6}}{[1+\frac{\gamma-1}{2} M_6{}^2]^{\frac{\gamma}{\gamma-1}}} = \frac{P_{T0}}{[1+\frac{\gamma-1}{2} M_0{}^2]^{\frac{\gamma}{\gamma-1}}} \qquad (5)$$

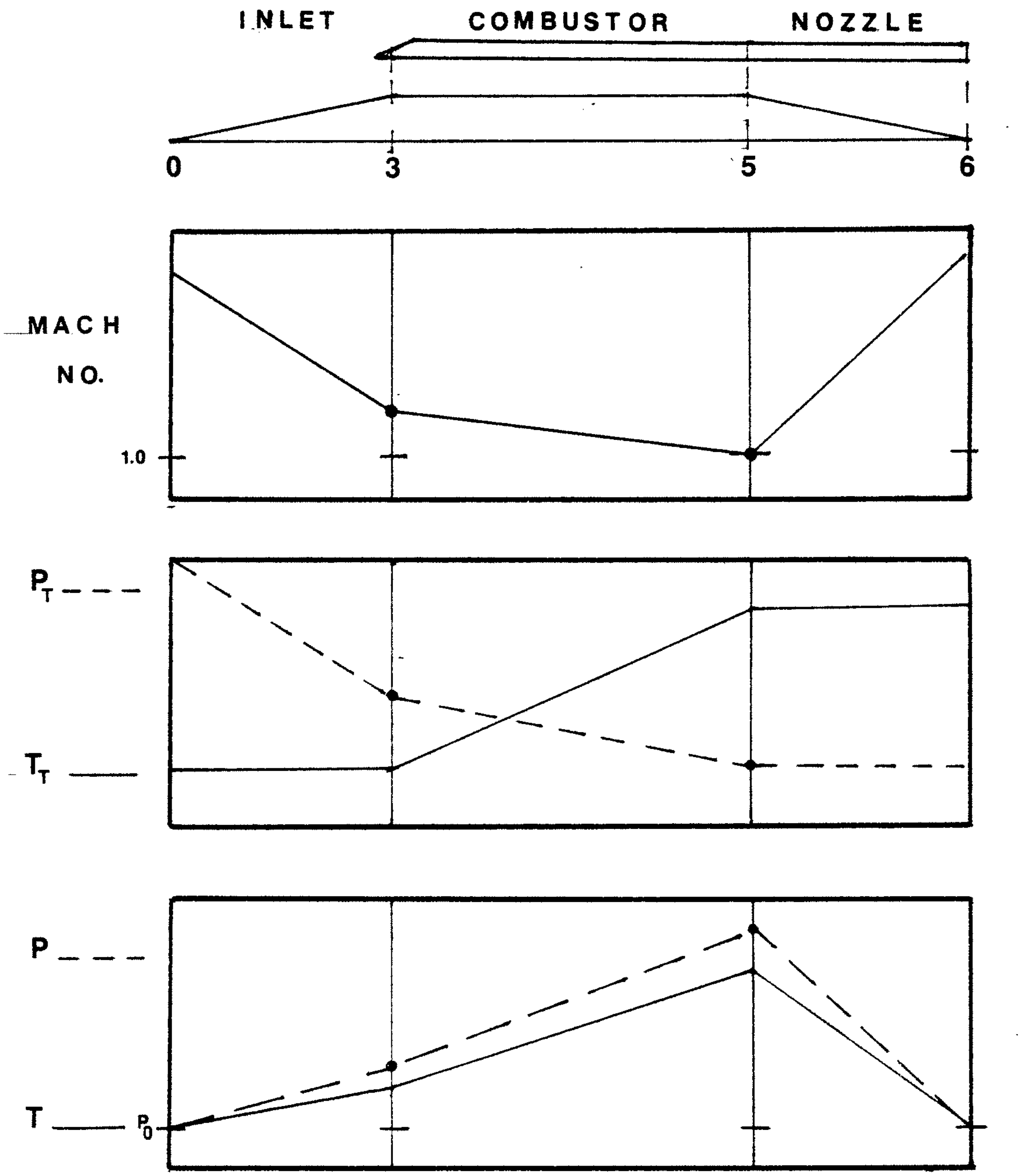


Fig. 3: IDEAL SCRAMJET CHARACTERISTICS
NOT DRAWN TO SCALE

From equations (4) and (5):

$$\frac{P_{T0}(\pi_n\ \pi_b\ \pi_b)}{[1+\frac{\gamma-1}{2}\ M_6{}^2]^{\frac{\gamma}{\gamma-1}}} = \frac{P_{T0}}{[1+\frac{\gamma-1}{2}\ M_0{}^2]^{\frac{\gamma}{\gamma-1}}} \tag{6}$$

Let

$$\pi = [\pi_n\ \pi_b\ \pi_d]^{\frac{\gamma-1}{\gamma}} = \frac{1+\frac{\gamma-1}{\gamma}\ M_6{}^2}{1+\frac{\gamma-1}{\gamma}\ M_0{}^2} \tag{7}$$

and $TR = 1 + [(\gamma+1)/2]\ M_0{}^2$.

Solving equation (7) for $(M_6/M_0)^2$ and relating Mach number and temperatures, results in equation (8).

$$(\frac{M_6}{M_0})^2 = (\frac{V_6}{V_0})^2)\ \frac{T_0}{T_6} = \frac{1}{TR-1}\ (TR\cdot\pi-1) \tag{8}$$

The energy equation across the combustor is

$$\dot{Q} + \sum_{inlet} \dot{m}_i h_{Ti} = \sum_{exhaust} \dot{m}_e\ h_{Te} \tag{9}$$

where $\dot{Q}$ = [fuel flow rate]x[chemical energy of the fuel ($h_f$, BTU/lbm)]x[the combustion efficiency ($\eta_b$)]. Applying the definitions above to the energy equation produces equation (10).

$$f\ h_f\ \eta_b + h_{T3} = (1+f)\ h_{T6} \tag{10}$$

By relating the stagnation temperature to the enthalpy by $h_T = C_P T_T$, and solving for the fuel-air ratio, f, equations (11) and (12) may be written as:

$$C_P T_{T0} = f\ h_f\ \eta_b = (1+f) C_P T_{T6} \tag{11}$$

$$f = \frac{\frac{T_{T5}}{T_{T0}} - 1}{\frac{h_f \eta_b}{C_P T_{T0}} - \frac{T_{T5}}{T_{T0}}} \tag{12}$$

As indicated in Figure 3, the stagnation temperature, $T_T$, at point 0 is equal to the stagnation temperature at point 3, therefore, from equation (12):

$$\frac{T_{T5}}{T_{T0}} = \frac{T_{T5}}{T_{T3}} = 1 + \frac{f h_f \eta_b (1+f)}{C_P T_{T0}} \tag{13}$$

Solving for the Mach number at point 5 from equation (13):

$$M_5^{\,2} = \frac{(1-2\gamma M_3^{\,2}K) + \sqrt{1-2KM_3^{\,2}(\gamma+1)}}{(2M_3^{\,2}\gamma^2K-\gamma-1)} \tag{14}$$

where

$$K = \frac{T_{T5}}{T_{T0}} \left(\frac{1+\frac{\gamma-1}{2}M_3^{\,2}}{(1+\gamma M_3^{\,2})^2}\right) \tag{15}$$

Now $\pi_b$ may be expressed as:

$$\pi_b = \frac{P_{T5}}{P_{T3}} = \frac{1+\gamma M_3^{\,2}}{1+\gamma M_5^{\,2}} \left(\frac{1+\frac{\gamma-1}{2}M_5^{\,2}}{1+\frac{\gamma-1}{2}M_3^{\,2}}\right)^{\frac{\gamma}{\gamma-1}} \tag{16}$$

In evaluating $\pi_d$, the kinetic energy efficiency of the diffuser, $\eta_d$, is defined by stream velocity at point 3, $V_3$, divided by the free stream velocity, $V_0$, quantity squared. This assumes isentropic expansion to the free stream pressure $P_0$ for a given $h_{T3}$ and $P_{T3}$ [Ref. 8]. As developed by G. L. Dugger [Ref. 8], given $M_3$, $P_{T3}$ may be determined from:

$$\eta_d = 1 - \frac{\left(\frac{P_{T0}}{P_{T3}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{\gamma-1}{2} M_0^{\ 2}\right)}$$

Therefore $\pi_d$ may be expressed as:

$$\pi_d = \left(1 + \frac{\gamma-1}{2} M_0^{\ 2} \ (1-\eta_d)\right)^{-\left(\frac{\gamma}{\gamma-1}\right)} \tag{17}$$

$P_{T6}/P_{T5}$, $\pi_n$, is assumed to be equal to 0.9.

$$F = \dot{m}_6 V_6 - \dot{m}_0 V_0 + A_6(P_6 - P_0) \tag{18}$$

The general equation of thrust for an air breathing engine, above, may be written as equation (22) by assuming complete expansion in the nozzle such that $P_6 = P_0$. Then writing F as,

$$F = \dot{m}_0 V_0 \ \left(\frac{\dot{m}_6 V_6}{\dot{m}_0 V_0} - 1\right) \tag{19}$$

and noting that from equation (8)

$$\frac{V_6}{V_0} = \frac{M_6}{M_0} \sqrt{\frac{T_6}{T_0}} = \sqrt{\frac{1}{TR-1}(TR \cdot \pi - 1) \ \frac{T_6}{T_0}} \tag{20}$$

$\dot{m}_6 = \dot{m}_{air} + \dot{m}_{fuel}$ such that $\dot{m}_6/\dot{m}_0 = (1+f)$ by definition. Substituting equations (13) and (7) into the expression for $T_6/T_0$ in terms of stagnation temperature results in:

$$\frac{T_6}{T_0} = \frac{1 + \dfrac{f\ h_f \eta_b}{C_P T_{T0}}}{\pi(1+f)} \tag{21}$$

Combining and simplifying equation (19), (20), and (21) results in equation (22).

$$F = \dot{m}_0 V_0 \left( \sqrt{\frac{(1+f)(TR\cdot\pi-1)(1+\dfrac{f\eta_b h_f}{C_P T_{T0}})}{\pi(TR-1)}} -1 \right) \tag{22}$$

Equation (22) is the expression for thrust produced by a scramjet as a function of $M_0$, $M_3$, losses in the engine $\pi$, $f$, $\eta_b$, $h_f$, $\dot{m}_0$, and $T_{T0}$.

The equations for thrust as a function of altitude $M_0$ and $M_3$, were programmed for a TI-59 calculator. See Appendix A for program listing. The atmospheric variable, $\rho_0$ (air density lbm/ft$^3$), $T_0$ (static air temperature, °R) and $a_0$ (sonic velocity, ft/sec) were entered for each altitude from tables of the ICAO STANDARD ATMOSPHERE [Ref. 9].

Though liquid hydrogen would provide a greater $I_{sp}$, a carbon-based fuel is used in this model. Carbon-based

fuels, like JP-5, $C_{10}H_{19}$, may be easily adapted to shipboard storage and have a significant density advantage over liquid hydrogen. The density of the fuel utilized is critical in this volume-limited system. The $h_f$ used in these calculations is 18630 Btu/lbm. The flame temperature in the combustor, $T_5$, for JP-5 in air at 1500°R and 40 atmospheres is approximately 5000°R. The air temperature and pressure are approximations for conditions of point 3 when $M_0$ is Mach 6 at sea level. The theoretical stoichiometric f for JP-5 is 0.0687; f for the maximum flame temperature above is 0.0733. The flame temperature, $T_5$, of 5000°R is used as a limiting factor in the thrust equation.

The thrust program, illustrated in Figure 4 and summarized in Table I, is a decremental-loop program which decrements the value of f and then determines; one, if $M_5$ can be calculated; two, if $M_5$ is approximately equal to 1.0; and three, if $T_5$ is within the limits for combustion of JP-5. Failure of any of the three tests results in a reduction of f and another attempt at calculating the thrust. The test for $M_5 \geq 1$ causes the thrust to be determined for thermally choked flow at point 5. Thermally choked flow for a constant area combustor provides maximum thrust and over-all engine efficiency [Ref. 8].

b. Inlet

A significant factor governing the amount of thrust produced is the Mach number of the flow at point 3,

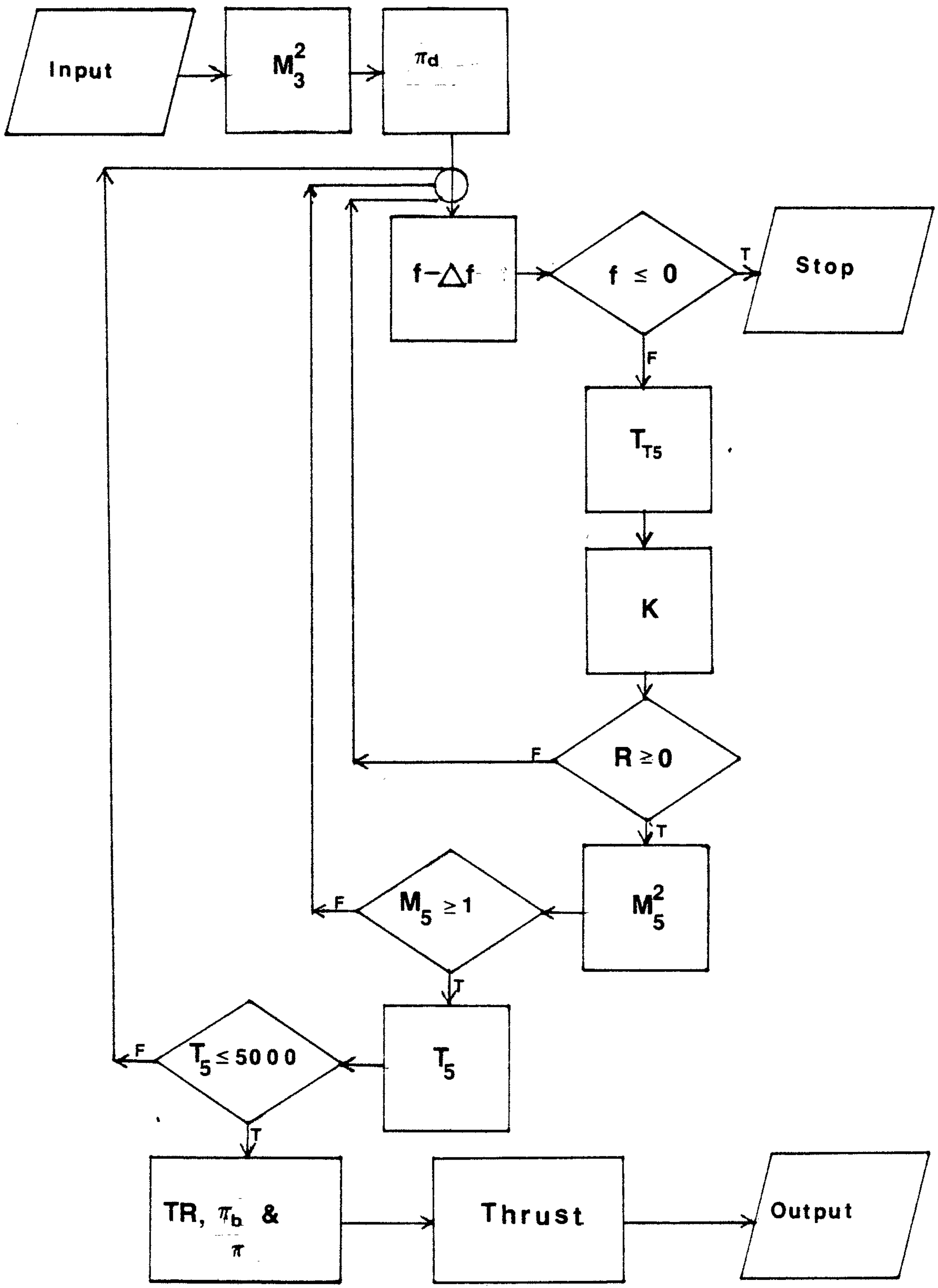


Fig. 4: SCRAMJET THRUST PROGRAM, LOGIC FLOW CHART

TABLE I

SUMMARY OF SCRAMJET THRUST PROGRAM EQUATIONS

$$\pi_d = (1+0.2M_0^{\,2}(1-\eta_d)^{3.5}$$

$$M_3 = 0.7M_0$$

$$\eta_b = 0.982$$

$$T_{T5} = \frac{(f\ 76950+T_{T0})}{(1+f)}$$

$$K = (\frac{T_{T5}}{T_{T0}})\ (\frac{1+0.2M_3^{\,2}}{(1+1.4M_3^{\,2})^2})$$

$$R = (1-4.8KM_3^{\,2})$$

$$M_5 = \sqrt{\frac{2.8M_3^{\,2}K-1-\sqrt{R})}{(0.4-3.92M_3^{\,2}K)}}$$

$$TR = (1+0.2M_0^{\,2})$$

$$\pi_b = \frac{(1+1.4M_3^{\,2})}{(1+1.4M_5^{\,2})}\ [\ \frac{(1+0.2M_5^{\,2})}{(1+0.2M_3^{\,2})}\ ]^{3.5}$$

$$\pi = (\pi_n\ \pi_b\ \pi_d)^{0.286}$$

$$F = \rho_0 A V_0^{\,2}\ [\sqrt{\frac{(1+f)(TR\cdot\pi-1)(1+\frac{f\eta_b h_f}{C_P T_{T0}})}{\pi(TR-1)}}\ -1]$$

$M_3$. Thrust was maximized for this scramjet by calculating thrust as a function of $M_3$ for various values of $M_0$, see Figure 5. Thrust was found to be maximized when $M_3/M_0 \simeq 0.7$. Figure 5 was determined for sea level; however, the results were determined to be reasonably consistent at various altitudes.

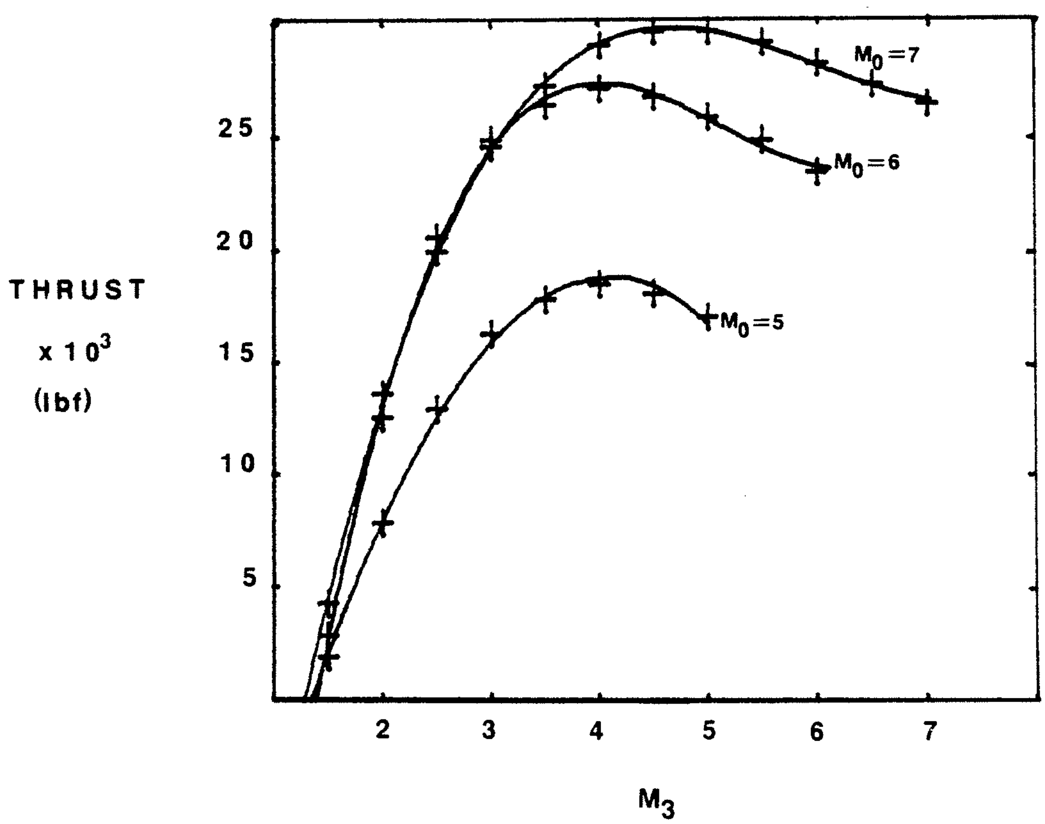


Fig. 5: SCRAMJET THRUST AS A FUNCTION OF THE MACH NUMBER AT POINT 3, $M_3$

The kinetic efficiency of the diffuser $\eta_d$ was determined with the equation $\eta_d = 0.94 + 0.06M_3/M_0$. This

equation assumes perfect air through a 3 oblique shock inlet with wedge angles of 10 to 15 degrees for Mach numbers from 3.0 to 7.0 [Ref. 8].

c. Scramjet Thrust Data

The thrust produced by the scramjet was calculated as a function of $M_0$ and altitude with the following variables set to the values indicated:

$\eta_d$ = 0.982

A = 1.2 ($ft^2$) inlet area

$\eta_n$ = 0.90

$T_5$ (MAX) = 5000°R

$h_f$ = 18630 (Btu/lbm)

f (stoichiometric) = 0.0687

$\eta_b$ = 0.95

$M_3$ = $0.7M_0$

The results are presented in Appendix B.

d. Curve Fit for Scramjet Performance

Calculation of the boost vehicle performance requires the values for thrust and fuel flow at each point along the flight path. The increment loop nature of the thrust program makes its incorporation into a flight path program undesirable. Fortunately, the plots of thrust and f as a function of Mach number and altitude are adequately represented by a series of straight lines. Figure 6 presents the correlation between the calculated data points, which are

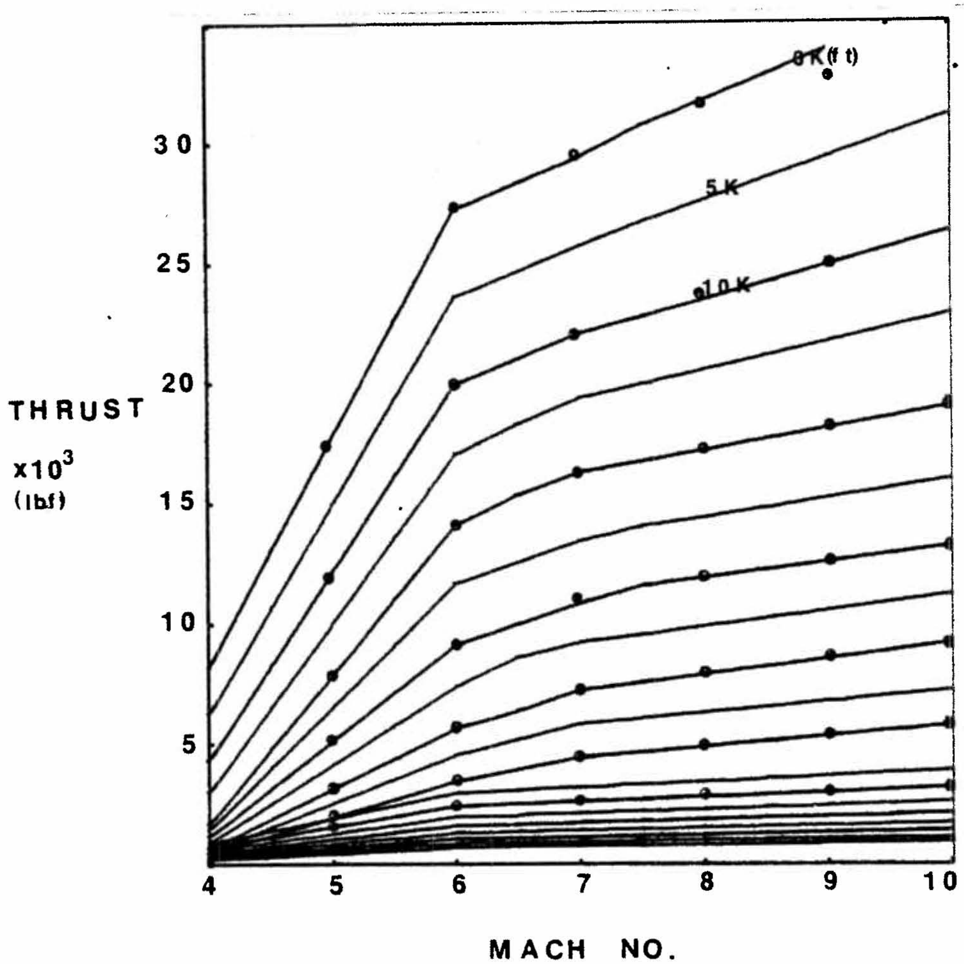


Fig. 6: SCRAMJET THRUST AS A FUNCTION OF MACH NUMBER AND ALTITUDE

shown as large dots calculated with the TI-59 thrust program, and the thrust curves calculated with the linear equations based on the thrust data. The linear equations for thrust are rather tedious and may be found in the program listing, Appendix C. The graph of f as a function of Mach number and altitude, shown in Figure 7, indicates that f may be approximated by three linear equations:

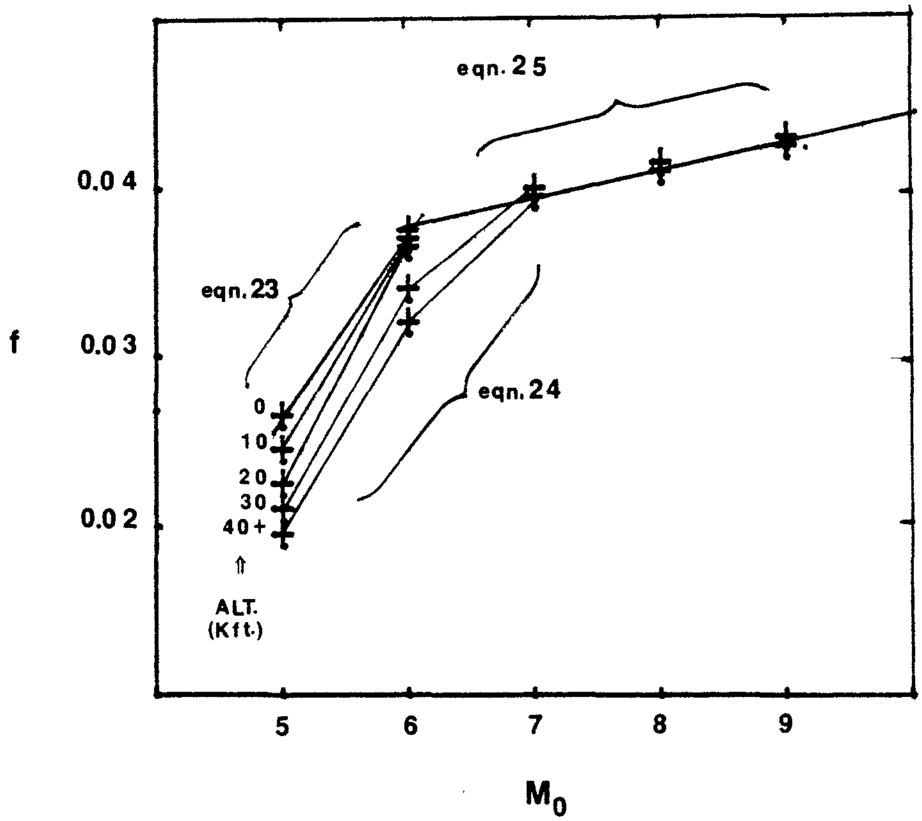


Fig. 7: FUEL-AIR RATIO, f, AS A FUNCTION OF THE MACH NUMBER AT POINT 0, $M_0$, AND ALTITUDE WITH CORRELATION TO APPROXIMATING EQUATIONS (23), (24), (25)

$$f = 0.011(M-5) + 0.0266$$
where $4 \le M_0 < 6$ and altitude < 30,000 ft. (23)

$$f = 0.0093(M-5) + 0.021$$
where $4 \le M_0 < 7$ and altitude > 30,000 ft. (24)

$$f = 0.0017(M-6) + 0.037$$
where 1) $M_0 > 6$, altitude < 30,000 ft.
2) $M_0 > 5$, altitude > 30,000 ft. (25)

e. Scramjet Vehicle Design

A complete and thorough design for a gun-launched ASAT using a scramjet far exceeds the scope of this thesis. However a general dimensional presentation is required to determine aerodynamic characteristics as well as fuel and payload volume capacity.

The three-dimensional parameters that generally define the shape and size of the vehicle are outer diameter, inner diameter and length. The outer diameter is established by the gun which is 16 inches if the gun is unaltered and 16.5 if the rifling is removed. Total length assuming the capability of performing some assembly of diffuser and tail section in the gun turret should be a maximum of about 16 feet. The inner diameter refers to the diameter of the cylindrical inner body which houses the payload, fuel and the vehicle controls. The inner diameter (i.e., the diameter of the center body) is influenced by two factors. The first factor is a result of the design characteristics of the diffuser. A minimum area at point 3, $A_3$, exists with regards to the free stream capture area, $A_0$, and $M_0$. Continuing with the assumptions of ideal gas, $M_3/M_0 = 0.7$ and $\eta_d = 0.982$ the ratio $A_3/A_0$ may be obtained as follows: by continuity $\dot{m}_0 = \dot{m}_3$ such that $A_3/A_0 = (P_0/P_3)(M_0/M_3)(A_0/A_3)$. From the relationships for ideal gas the $T_{T0} = T_{T3}$, $P_{T0}/P_{T3} = 1/\pi_d$ the ratio of $A_3/A_0$ may be written as:

$$\frac{A_3}{A_0} = \frac{1}{\pi_d} \frac{M_0}{M_3} \left( \frac{1+\frac{\gamma-1}{2} M_3^{\,2}}{1+\frac{\gamma-1}{2} M_0^{\,2}} \right)^{(\frac{\gamma}{\gamma-1} - 1)} \tag{26}$$

Evaluating $1/\pi_d$ with equation (17) and applying the assumptions above, $A_3/A_0$ may be calculated as a function of $M_0$. At this point, an assumption must be made about the thickness of the outer case illustrated in Figure 8. Obviously, for a fixed $A_0$, the ratio of the diameter of the center body to free stream capture area, $A_3/A_0$, must decrease as the outer case thickness increases. Therefore, at least two options exist. The first option is to make the outer case thick enough to hold the fuel and controls. The second option minimizes the thickness of the outer case and carries all fuel and controls in the center body. The payload section will necessarily be located in the center body of the boost vehicle. The center body is required to be at least 13 inches in diameter to accommodate the existing ASAT MV or have sufficient volume to accommodate a volume-equivalent ASAT MV. Option two is therefore applicable.

If the outer case wall is assumed to be 0.5 inches thick, the area within the outer case is 176.7 square inches. For an $A_0$ of 153.9 square inches and flight Mach numbers of 4.5 to 9.0, $A_3$ will vary from 61.56 to 96.96 square inches.

Assuming the variable geometry of the inlet assembly is capable of reducing $A_3$ from its maximum to its

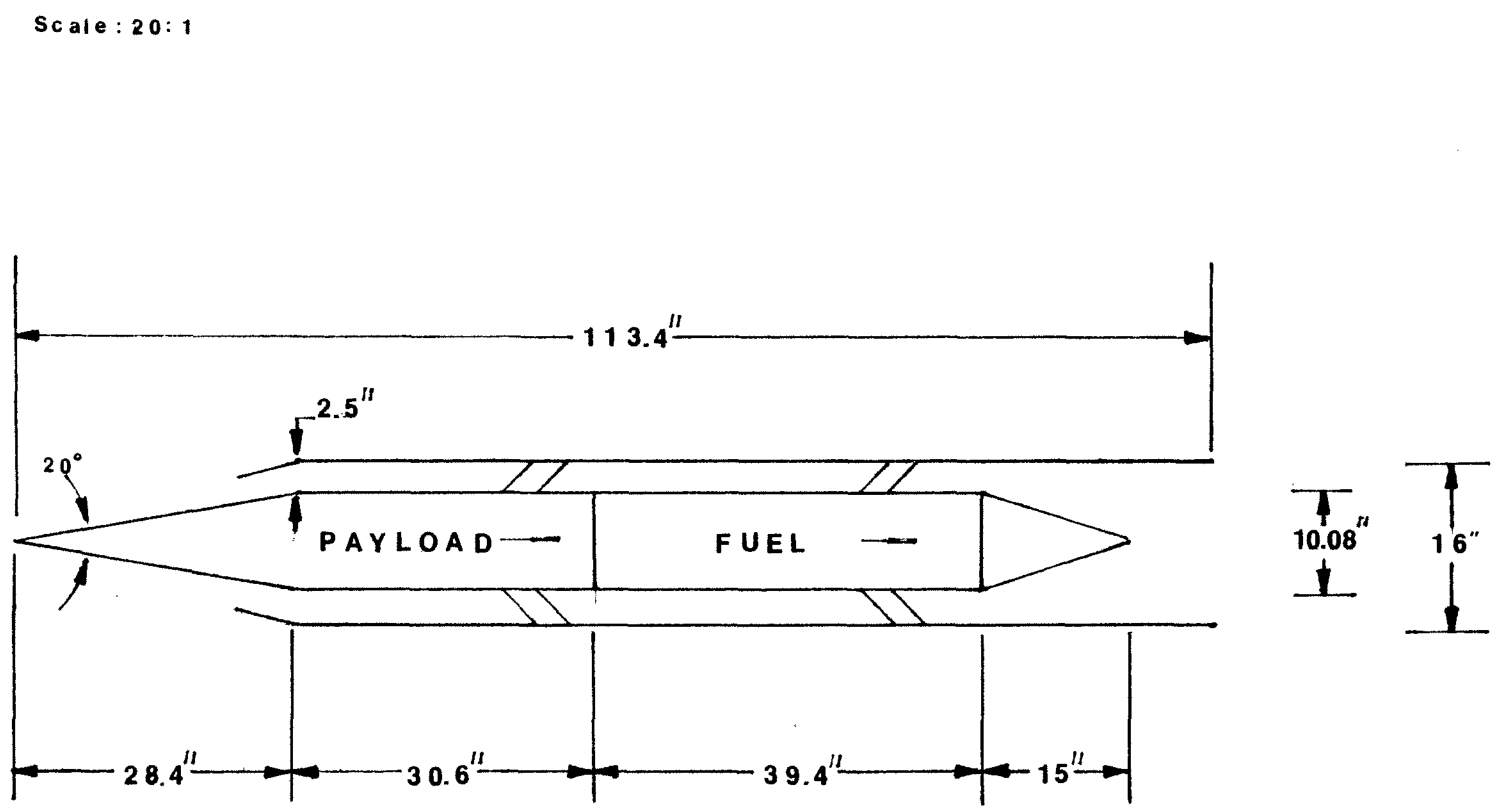


Fig. 8: GUN-LAUNCHED SCRAMJET ASAT WEAPON

minimum value, the maximum center body area must be small enough to provide for the maximum $A_3$. Consequently, the center body is limited to a 10.08 inch diameter.

As the dimensions of the center body will not accommodate the existing ASAT MV, a volume-equivalent payload of 2261 cubic inches will be used. This volume includes the 12 x 13 inch cylindrical MV and an additional 790 cubic inches of auxillary equipment.

Figure 8 is a general representation of a potential gun-launched scramjet ASAT vehicle. The volume equivalent payload will occupy the 309 cubic inches of the diffuser cone as well as a 30.6 inch section of the center body. This assumes 0.5 inch thick walls and a 10.08 inch diameter center body.

The scramjet engine was modeled using JP-5 as a typical fuel. JP-5 has a density of 0.0296 $lbm/in^3$. Therefore, to carry 100 lbm of fuel requires 3376.3 cubic inches; based on center body diameter, the volume corresponds to a 52.6 inch long section of center body. If a high density carbon based fuel, similar to the fuels being developed for various cruise missile applications, is used, a fuel density of 0.0397 $lbm/in^3$ may be assumed [Ref. 10]. The center body length required for fuel is then reduced to 39.4 inches. The vehicle case including structure and insulation is assumed to have an average density of 0.0367 $lbm/in^3$. The assumed total case mass is 356.33 lbm. Fuel

allotted is 110.23 lbm. The payload, which includes the MV, and support equipment, is allotted 100 lbm. Control and guidance equipment which includes diffuser control, fuel control and control surfaces actuators is allotted 150 lbm. Vehicle total launch weight is 716.5 lbm.

B. ROCKET

1. Rocket Background

Gun launched sounding rockets have been developed and tested as part of several projects. During the late 60's and early 70's, the Gun-Launched-Orbitor, (GLO-1A), was developed [Ref. 2]. The GLO-1A was a three stage system designed to be fired from a 16.7 inch, 75 caliber gun. The predicted apogee with a 8.6 lbm payload was 2629 nm. Applying this promising performance to the ASAT problem resulted in the following model.

2. Rocket Model

The rocket boosted gun-launched ASAT is a simple, single stage, fin-controlled system. The design assumes a smooth bore oversized gun barrel. The vehicle is assumed to be 16.5 inches in diameter. If a silicon greased nylon, or teflon obturator, is used, the barrel will be approximately 16.7 inches in diameter.

a. Rocket Thrust

The propellant grain is 40 x 16 inches, end inhibited, with an internal eight point star. A possible propellant is DB/AP-HMX/Al, which has a density of 0.067

$lbm/in^3$. The boost grain mass is 472.2 lbm or 216 Kg. For the purposes of this model, thrust is assumed to be constant and equal to the average thrust. The average thrust, T, is equal to 19010 lbf or 84556.48 Nt. The $I_{sp}$ is 243 sec. Propellant mass burn rate is 78.7 lbm/sec or 36 Kg/sec. Assuming the action time equals the burn time, the boost grain is modeled to produce the average thrust for 6 seconds. The model also assumes complete expansion in the nozzle.

b. Rocket Vehicle Design

The diameter of the rocket boost vehicle will allow the use of the MV developed for the Air Force. As illustrated in Figure 9, a 12-inch long section of vehicle is allotted for the MV. Additionally, 2421 cubic inches are available in the nose cone for auxiliary equipment. The payload mass in the rocket system is the same as the scramjet system, 100 lbm. The weight of the vehicle case and controls, based on the values given for the GLO-1B [Ref. 2] is 184.4 lbm or 83.6 Kg. Total vehicle mass is 760.59 lbm or 345 Kg.

Scale; 20:1

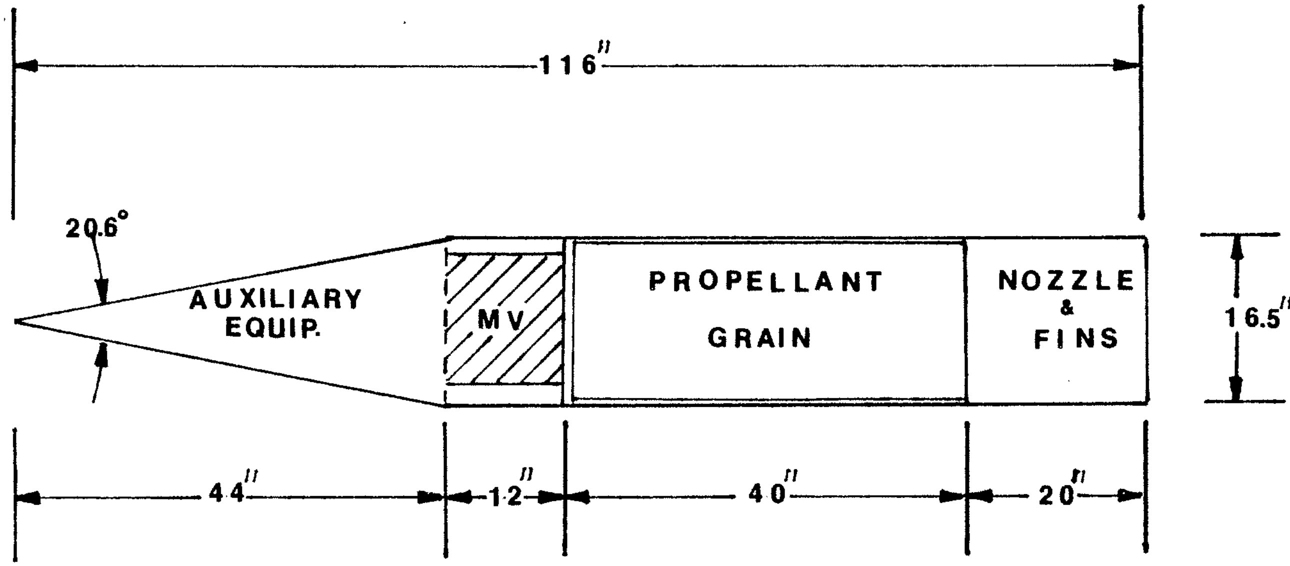


Fig. 9: GUN-LAUNCHED ROCKET ASAT WEAPON

# IV. HYPERSONIC AERODYNAMICS

Both the scramjet and the rocket boost vehicles exit the barrel at a high supersonic Mach number, 4.5, and rapidly accelerate to hypersonic speeds greater than Mach 5. Both vehicles are basically cone capped cylinders. As indicated in Figure 2, in order to maximize performance, the vehicles will need to increase their flight path angle, A, from the maximum gun launch angle of 45 degrees. The variables used in this section are those used in the trajectory program of Appendix C. Aerodynamic lift is used to achieve the change in trajectory angle. The change in trajectory angle is termed a pop-up maneuver. Therefore, the aerodynamic control system for the vehicle must be capable of providing an angle of attack, A7, as well as stabilizing the vehicle.

## A. HYPERSONIC AERODYNAMIC FORCES

One theoretical method of dealing with hypersonic aerodynamics is through the use of Newtonian impact theory. This entire section on hypersonic aerodynamics follows closely the presentation in Chapters 3 and 4 of Truitt [Ref. 11]. The basic assumption is that at extremely high Mach numbers the aerodynamic force coefficients are independent of the mach number. Aerodynamic forces on the body are a function of surface area presented to the free

stream. Comparison between impact theory predictions of force characteristics for a cone-cylinder body and experimental data at Mach 7 is of the same order of accuracy as obtained at lower Mach number with supersonic theory. Accuracy can be expected to increase with higher Mach numbers as the impact theory is derived for a free stream Mach number of infinity.

Three possible cases can be considered in determining the force coefficients for the body:

Case One - The angle of attack equals zero, A7 = 0.

Case Two - The angle of attack is less than or equal to the half cone angle, A7≤A3.

Case Three - The angle of attack is greater than the half cone angle, A7>A3.

Define the following symbols:

$C_N$ = normal force coefficient

$C_C$ = axial force coefficient

A3 = half cone angle (deg)

A7 = angle of attack (deg)

R9 = diameter of cone base = diameter of cylinder(inch)

$L_{DL}$ = length of cone (inch)

$L_{DS}$ = length of cone not considered for cowl (inch)

R0 = diameter of cowl opening (inch)

Using the cone shown in Figure 9, $A_3$ would be 10.3°.

1. Case One: A7 = 0

The cylinder is parallel to the free stream, therefore, $C_{N\ (Cyl)} = C_{C\ (Cyl)} = C_L = C_D = 0$. The cone presents a symmetrical surface to the free stream, therefore:

$$C_{C_{cone}} = 2 \sin^2 A3 \tag{27}$$

The normal force coefficient is equal and opposite at each opposing point on the cone such that $C_{N(Cone)} = 0$.

2. Case Two: A7≤A3

In this case, the entire cone is presented to the flow such that:

$$C_{N_{cone}} = \cos^2 A3 \sin 2A7 \tag{28}$$

and

$$C_{C_{cone}} = 2\sin^2 A3 + \sin^2 A7\ (1-3\sin^2 A3) \tag{29}$$

3. Case Three: A7>A3

Only a portion of the cone is presented to the free stream forming a low pressure shadow over the remainder of the surface. The area subject to free stream impact is described by:

$$B = \arcsin\left(\frac{\tan A3}{\tan A7}\right) \tag{30}$$

Then

$$C_{N_{cone}} = \cos^2 A3 \sin A7 [\frac{B+\frac{\pi}{2}}{\pi} + \frac{1}{3\pi}$$

$$x \cos B(\cot A7 \tan A3 + 2\tan A7 \cot A3)] \qquad (31)$$

and

$$C_{C_{cone}} = 2\sin^2 A3 + \sin^2 A7(1-3\sin^2 A3)(\frac{B+\frac{\pi}{2}}{\pi})$$

$$+ \frac{3}{4\pi} \cos B \sin 2A7 \sin 2A3 \qquad (32)$$

For both cases two and three, the force coefficient on the cylinder are represented by $C_C = 0$ and

$$C_{N_{cyl}} = \frac{5.33}{\pi} \frac{L9}{R9} \sin^2 A7 \qquad (33)$$

Equations (27) through (33) effectively describe the hypersonic forces on the rocket boost vehicle. However, the scramjet configuration, neglecting the diffuser cone, is best represented by a partial cone and a cylinder. The partial cone represents the scramjet cowl.

In modelling the cowl consider the cone divided into two cones. As illustrated by Figure 10, the large cone has a length, $L_{DL}$, and a base diameter of R9. The small cone has a length, $L_{DS}$, and a base diameter of R0. The cowl is

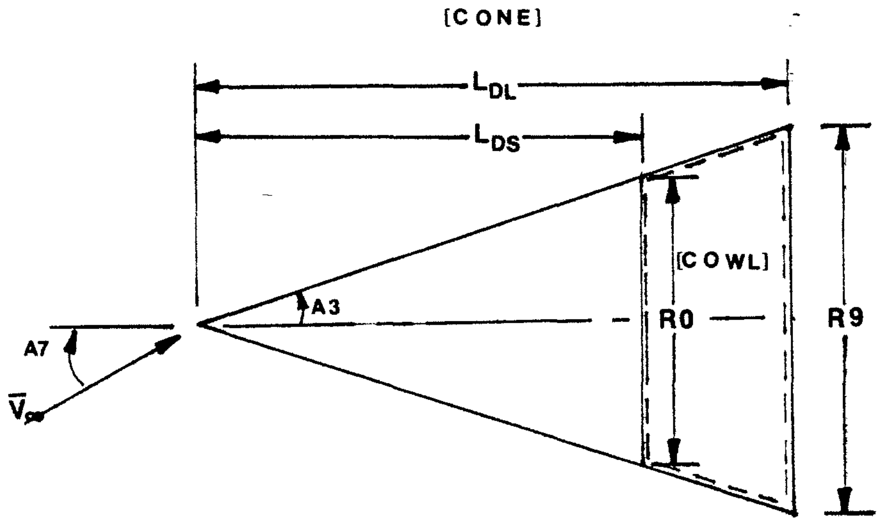


Fig. 10: CONE AND COWL

represented by the (large cone - small cone), and, therefore, has an inlet diameter of R0 and a base diameter of R9. Relating the $C_N$ on the cones for case two by the base area;

$C_{N_{\text{Small Cone}}} = \cos^2 A3 \sin 2A7$; base area $= \pi/4(R0^2)$

$C_{N_{\text{Large Cone}}} = \cos^2 A3 \sin 2A7$; base area $= \pi/4(R9^2)$.

$$C_{N_{\text{Cowl}}} = C_{N_{\text{Large Cone}}} - C_{N_{\text{Small Cone}}} \tag{34}$$

Converting to a common base area

$$C_{N_{\text{Small Cone}}} \left(\frac{\pi R0^2}{4} \frac{4}{\pi R9^2}\right) = \cos^2 A3 \sin 2A7 \tag{35}$$

The conversion factor for the forces on the cowl is:

$$(1 - (\frac{R0}{R9})^2) \tag{36}$$

4. <u>$C_D$ and $C_L$</u>

By multiplying equations (27), (28), (29), (31), (32) and (33) by equation (36), $C_{N\ (cowl)}$ and $C_{C\ (cowl)}$ may be determined for each case.

The coefficients of lift, $C_L$, and drag, $C_D$, for the cowl or cone are expressed in terms of the applicable value of $C_C$ and $C_N$. The general equations for $C_D$ and $C_L$ are:

Case One: $C_D = C_C = 2\sin^2 A3$ (27a)

Case Two and Case Three:

$$C_D = C_N \sin A7 + C_C \cos A7 \tag{37}$$

$$C_L = C_N \cos A7 - C_C \sin A7 \tag{38}$$

For the cylinder:

Case One: $C_D = C_N = C_C = 0$ (39)

Case Two and Case Three:

$$C_{D_{cyl}} = C_{N_{cyl}} \sin A7 \tag{40}$$

$$C_{L_{cyl}} = C_{N_{cyl}} \cos A7 \tag{41}$$

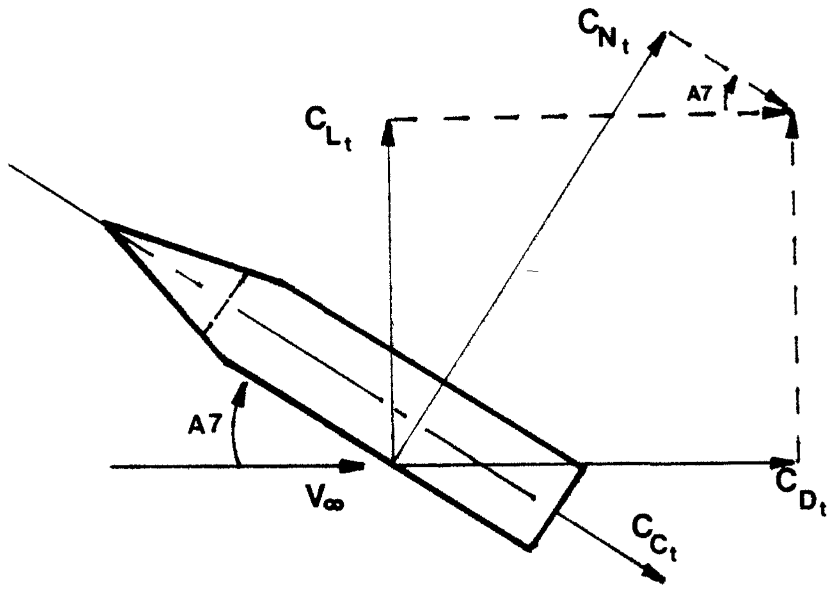


Fig. 11: AERODYNAMIC FORCE COEFFICIENTS

The total lift and drag coefficient due to the impact theory, as shown in Figure 11, is

$$C_{L_t} = C_L + C_{L_{cyl}} \tag{42}$$

$$C_{D_t} = C_D + C_{D_{cyl}} \tag{43}$$

In addition to impact drag, the coefficient of skin friction drag was determined for flow over the cylinder. The equations for skin friction as a result of laminar imcompressible flow over a flat plate were applied to a cylinder of length, L [Ref. 12].

$$C_{DF} = \frac{1.328\sqrt{\mu}}{\sqrt{\rho_0 V_o} L} \quad (44)$$

This model for boundary layer was selected to provide insight concerning magnitude of skin friction. A more refined analysis using theory appropriate for hypersonic flow is needed. Equation (43) then becomes:

$$C_{D_t} = C_D + C_{D_{cyl}} + C_{DF} \quad (43a)$$

B. CONTROLS

The control system on the vehicle must be capable of initiating and maintaining the required angle of attack to achieve and maintain the desired flight path angle until the vehicle is exoatmospheric. The flight path angle and velocity as the vehicle begins a vacuum trajectory will determine the apogee and the encounter geometry between the MV and the target satellite.

1. Forms of Control

There are two basic forms of control that may be used to control the vehicle, vectored thrust or aerodynamic control surfaces.

The vectored thrust approach could be achieved with external or internal reaction jets. The volume and weight

limitations of this system prevent the use of a separate engine to support the reaction jets. Therefore, the reaction jets would depend on bleed pressure from the booster. The rocket burns for only 6 seconds and the scramjet must burn most of its fuel at low altitudes for maximum efficiency. In both cases, there may be no thrust available for control while the vehicle is still subject to high dynamic pressures.

Two possible types of control surfaces are folding fins, similar to those used on the 5-inch guided projectile [Ref. 13], or storable flaps. The fins would fold at the base of the vehicle, adding to its length, and would deploy upon clearing the barrel.

The storable flap would be of the same contour as the vehicle body and would store flush with the body. The four evenly spaced flaps would be hinged on the forward edge with the rear edge elevated by an actuator. The effect would be similar to that of a variable geometry frustum. The advantage of the storable flap is that when control is not required, drag is not created by the control surface.

Any type of control surface used must be capable of withstanding the launch and up to 1,500,000 $N/m^2$ of in flight dynamic pressure.

# V. TRAJECTORY OPTIMIZATION

The gun-launched ASAT system was modeled on a HP-9830 computer. See Appendix C for the program listing. The program is designed to calculate the vehicle position, altitude, acceleration, thrust, weight, drag and lift once each time increment, t. Either the scramjet or the rocket boost vehicle described previously may be selected. Gun elevation, A, pop-up altitude, H1, angle of attack, A7, and maximum flight path angle, A8, are input variables. Thrust, F, fuel/air ratio, F8, drag, D, and lift, L, are calculated at each time increment with the equations developed in the previous chapters. The trajectories assume a flat earth. If a maximum apogee of 1000 Km is assumed, the error between flat earth and round earth calculations is about $\pm$ 5%.

## A. OPTIMUM SCRAMJET TRAJECTORY

The scramjet performance is related to the dynamic pressure. If the flight path is level and at a moderately low altitude, the scramjet is theoretically capable of rather phenomenal performance. As the flight path becomes steeper, and the vehicle rapidly gains altitude, the atmospheric oxygen available for combustion decreases. Therefore, the scramjet has less time to produce useful thrust. This makes the scramjet performance sensitive to the gun elevation angle, the pop-up altitude and the angle of attack.

A trial and error method was used to determine the optimum scramjet trajectory. The gun elevation angle was varied from 15 to 45 degrees in 5 degree increments. For each gun elevation angle, the angle of attack was varied from 0 to 12 degrees in 3 degree increments. This was done for various pop-up altitudes from 500 to 11,000 meters. The results are presented in Figure 12. The maximum apogee, 558 Km, results from a gun elevation angle of 15 degrees, a pop-up altitude of 6000 meters and an angle of attack of 12 degrees.

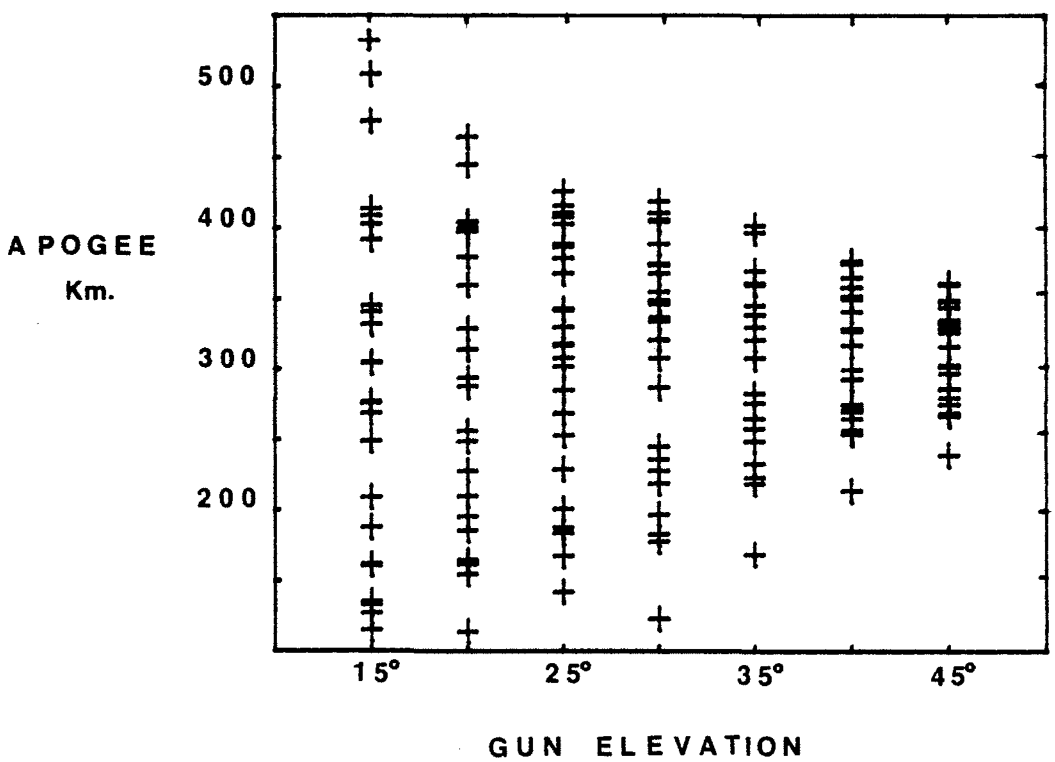


Fig. 12: SCRAMJET APOGEE AS A FUNCTION OF GUN ELEVATION FOR VARIOUS ANGLES OF ATTACK AND POP-UP ALTITUDES

The data spread indicates that as the gun elevation angle increases, the trajectory becomes less sensitive to the angle of attack and pop-up altitude. Appendix D presents the data used to produce Figure 12. Included are the angle of attack and pop-up altitude for each point.

Figures 13 and 14 represent the variation of apogee as a function of pop-up altitude and angle of attack at a given gun elevation.

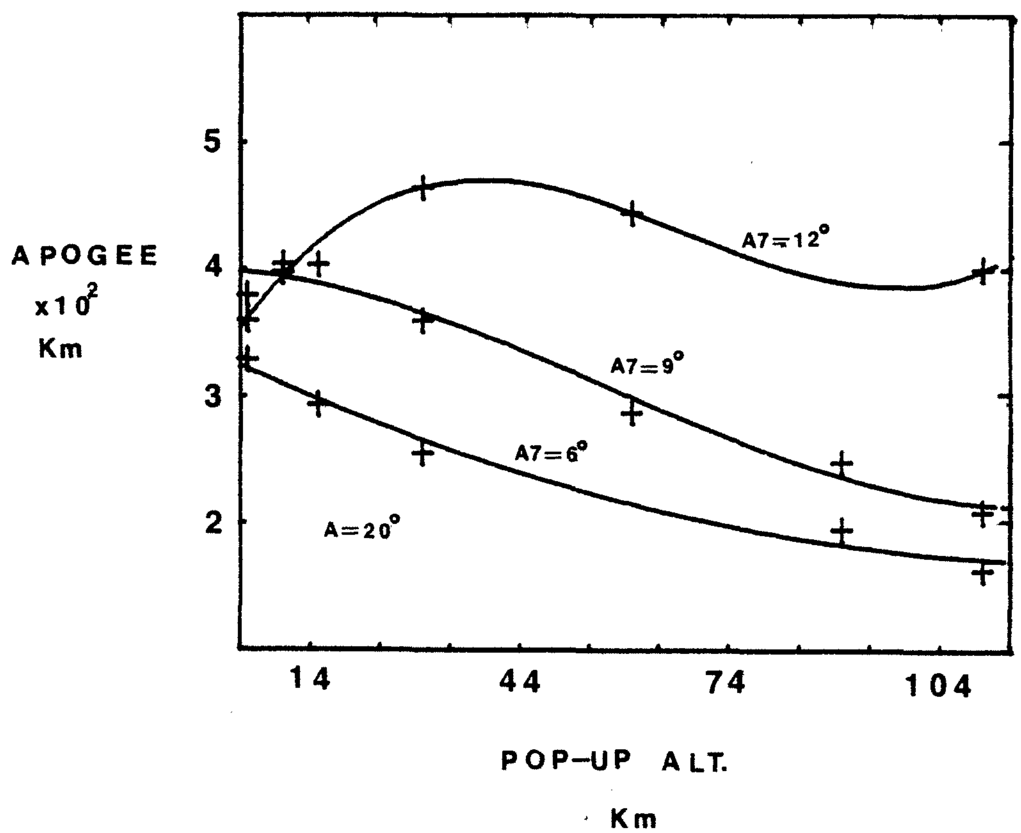


Fig. 13: SCRAMJET APOGEE AS A FUNCTION OF GUN ELEVATION, A, ANGLE OF ATTACK, A7, AND POP-UP ALTITUDE, A=20°

The A7 = 12° curve which appears in Figure 14, verifies the assumption that maximum performance for a gun elevation angle of 15 degrees and an angle of attack of 12 degrees occurs when the pop-up altitude is 6000 m.

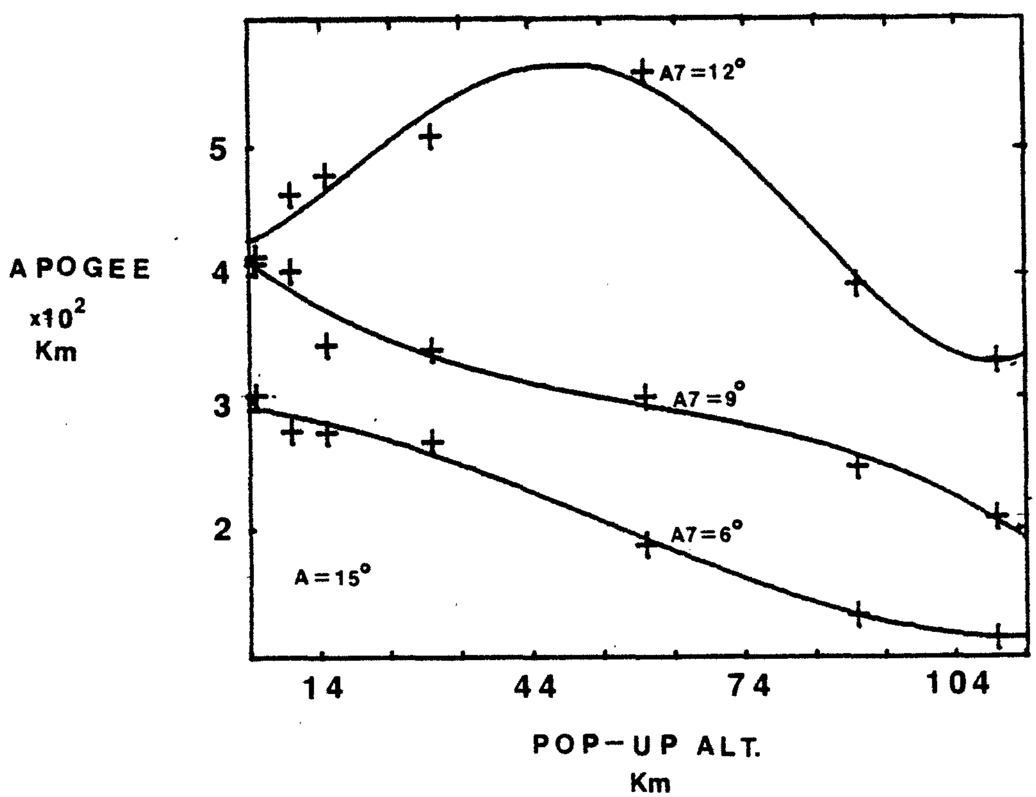


Fig. 14: SCRAMJET APOGEE AS A FUNCTION OF GUN ELEVATION, A, ANGLE OF ATTACK, A7, AND POP-UP ALTITUDE, A=15°

## B. OPTIMUM ROCKET TRAJECTORY

Determination of the optimum rocket trajectory is straight forward, relative to determining the scramjet optimum trajectory. The forces affecting the rocket are thrust, drag, and gravity. Thrust is assumed constant and of a 6 second duration. Gravity varies little over the altitude range under study and is considered constant, $g = g_0$. Drag decreases with altitude. From acceleration = force/mass where force = ($\vec{thrust}$ - $\vec{drag}$ - $m\vec{g}$) and mass decreases with time, to increase acceleration, drag must be decreased while thrust is still present. Increasing altitude as rapidly as possible is the obvious solution. Ideally the gun would be elevated to 90 degrees and the rocket fired immediately upon leaving the barrel. As a gun elevation of 90 degrees is not possible, the next best solution is to use the maximum gun elevation angle, 45 degrees, and pop-up as soon as feasible after leaving the barrel. If the pop-up altitude is 1000 m and the muzzle velocity is Mach 4.5, there are 0.7 seconds for the control system to become operative and for the rocket to ignite. The apogee achieved under these conditions is 928 Km. Table 2 is a listing of apogee as a function of pop-up altitude and angle of attack. The gun elevation angle is 45 degrees. Of particular interest is the first entry in Table 2. A simple rocket-boosted, 45-degree launch with no pop-up is capable of propelling the 45 Kg paylog to an altitude of 409 Km. Table 2 also shows that the apogee is insensitive to pop-up altitude up to about 2000 m.

Figure 15 represents the maximum apogee trajectory of the gun-launched scramjet ASAT. The program output for this trajectory is found in Appendix E.

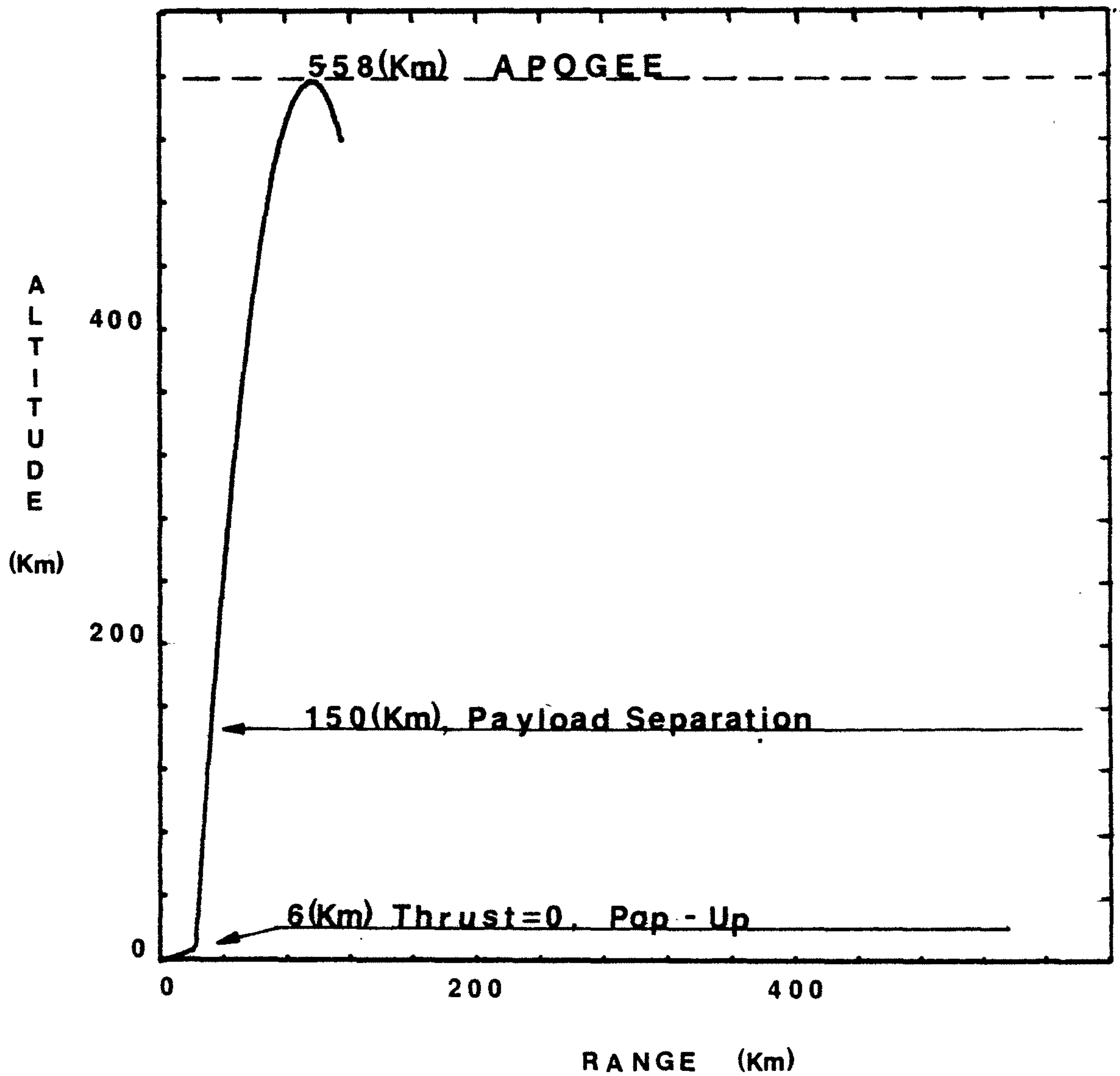


Fig. 15: SCRAMJET MAXIMUM APOGEE TRAJECTORY

TALBE II

APOGEE AS A FUNCTION OF ANGLE OF ATTACK AND POP-UP ALTITUDE FOR GUN-ELEVATION = 45°

| Angle of Attack (DEG) | Pop-up Altitude (m) | Apogee (Km) |
|---|---|---|
| 0 | 0 | 409 |
| 3 | 100 | 577 |
| 6 | 100 | 753 |
| 9 | 100 | 800 |
| 12 | 100 | 928 |
| 3 | 300 | 577 |
| 6 | 300 | 753 |
| 9 | 300 | 800 |
| 12 | 300 | 928 |
| 3 | 1000 | 577 |
| 6 | 1000 | 753 |
| 9 | 1000 | 800 |
| 12 | 1000 | 928 |
| 3 | 3000 | 554 |
| 6 | 3000 | 716 |
| 9 | 3000 | 774 |
| 12 | 3000 | 828 |
| 3 | 6000 | 531 |
| 6 | 6000 | 673 |
| 9 | 6000 | 743 |
| 12 | 6000 | 909 |

If a comparison is made of flight parameters at an arbitrary point, 100 Km, where the dynamic pressure can be assumed to be zero, the Mach number and flight path angle of a shot with an angle of attack of 3 degrees and a pop-up altitude of 100 - 1000 m, are 13.1 and 53.3 degrees. For the same shot with an angle of attack of 12 degrees the Mach number is 14.0 and the flight path angle is 81 degrees. By executing a 40-g pop-up, the vehicle avoids a great deal of drag and achieves greater acceleration, as previously assumed.

Figure 16 represents the maximum apogee trajectory of the gun-launched rocket ASAT. The program output for this trajectory is found in Appendix E.

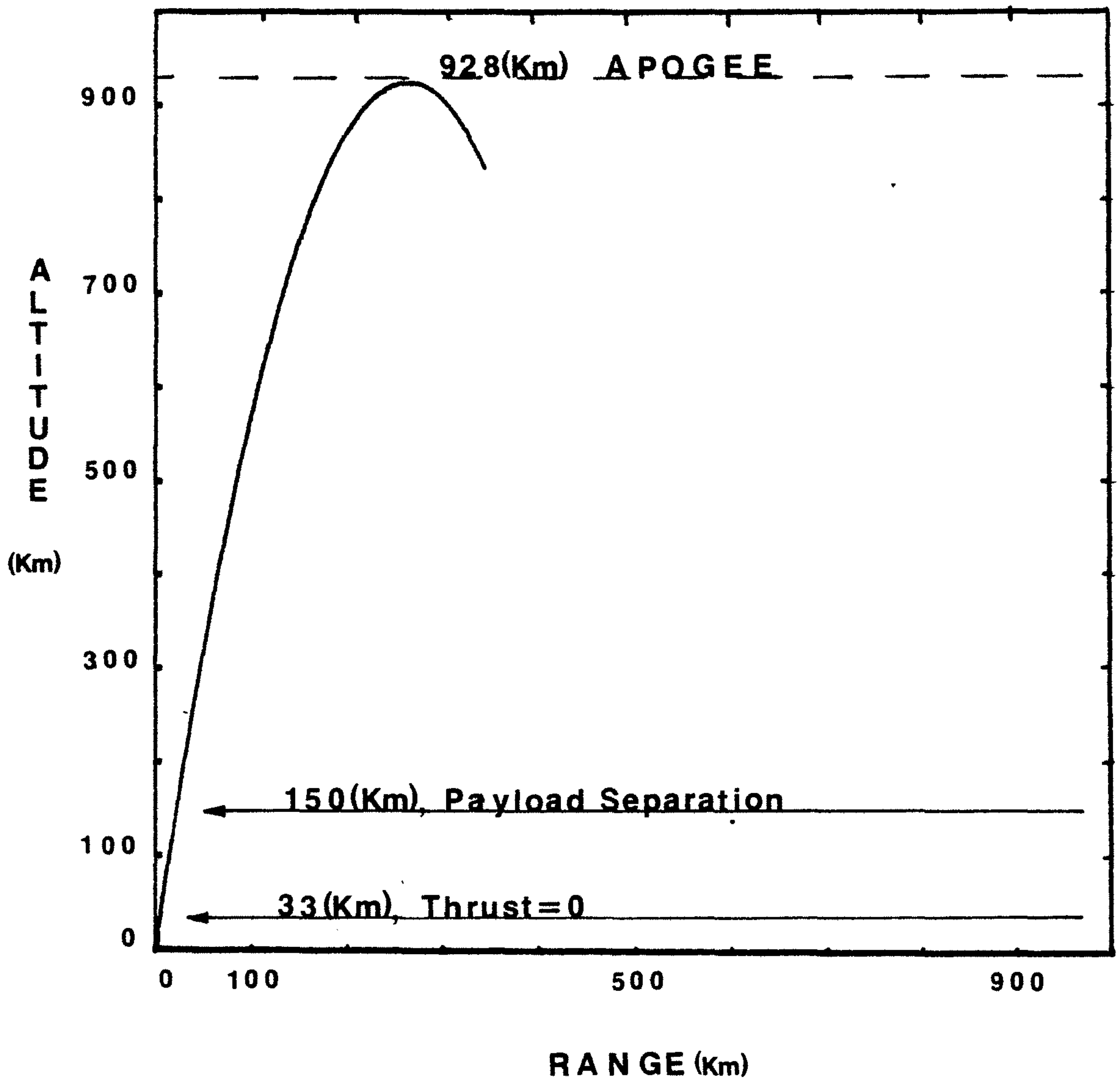


Fig. 16: ROCKET MAXIMUM APOGEE TRAJECTORY

# VI. CONCLUSIONS

The design and development of a 16-inch gun-launched anti-satellite weapon is theoretically feasible. Given proper targeting information and assuming the MV can be configured for gun launching, a rocket or scramjet gun-launched vehicle can boost the ASAT payload to altitudes at which a RORSAT or EORSAT may be intercepted.

The air-breathing scramjet has a greater $I_{sp}$ than does the rocket; however, the scramjet thrust is altitude limited. The rocket can take advantage of a farvorable thrust-to-drag ratio at higher altitudes.

The need for an inlet on the scramjet complicates payload placement and limits the volume available for fuel. The greater density of the rocket propellent better utilizes the volume available.

The rocket boost vehicle requires few advances in design technology, and the maximum apogee of 928 Km for the rocket ASAT with same payload as the scramjet ASAT indicates that heavier payloads may be delivered by a rocket ASAT to the altitudes of interest, 250 -440 Km. The ability of the rocket boost vehicle to intercept satellites up to 409 Km, without executing a pop-up manuever, indicates that a very simple, possible spin-stabilized vehicle, can be developed to counter the low altitude threat.

# APPENDIX A

## PROGRAM LISTING FOR SCRAMJET THRUST

This is a listing for a TI-59 program that will, for a given altitude, calculate the thrust for a scramjet. The program executes in a closed loop, calculating the thrust for the initial Mach number, incrementing the Mach number by one and recalculating the thrust.

The memory loading prior to execution of the program:

| Memory | Variable | Value | Comment |
|---|---|---|---|
| 03 | $\eta_d$ | 0.97 | |
| 04 | $P_0$ | ---- | Air density ($lbm/in^3$) |
| 06 | A | 1.24 | inlet area ($ft^2$) |
| 07 | $\pi_n$ | 0.9 | |
| 09 | $h_f$ | 18630 | Btu/lbm |
| 15 | f | 0.0676 | |
| 21 | $\Delta f$ | -0.0005 | |
| 25 | $T_0$ | ---- | static air temp. (°R) |
| 26 | $a_0$ | ---- | sonic speed (ft/sec) |

Place initial Mach number in register and press A' to execute.

```
000  76 LBL
001  11  A
002  53  (
003  01  1
004  85  +
005  93  .
006  02  2
007  65  X
008  43 RCL
009  02  02
010  33 X²
011  65  X
012  53  (
013  01  1
014  75  -
015  43 RCL
016  03  03
017  54  )
018  54  )
019  45 YX
020  03  3
021  93  .
022  05  5
023  94 +/-
024  95  =
025  42 STO
026  13  13
027  68 NOP
028  43 RCL
029  02  02
030  65  X
031  93  .
032  07  7
033  95  =
034  33 X²
035  42 STO
036  14  14
037  68 NOP
038  68 NOP
039  68 NOP
040  68 NOP
041  68 NOP
042  68 NOP
043  68 NOP
044  68 NOP
045  68 NOP
046  68 NOP
047  68 NOP
048  76 LBL
049  17 B'
050  43 RCL
051  21  21
052  44 SUM
053  15  15
054  25 CLR
055  32 X:T
056  43 RCL
057  15  15
058  22 INV
059  77  GE
060  19 D'
061  53  (
062  43 RCL
063  15  15
064  65  X
065  07  7
066  06  6
067  09  9
068  05  5
069  00  0
070  85  +
071  43 RCL
072  01  01
073  54  )
074  55  ÷
075  53  (
076  01  1
077  85  +
078  43 RCL
079  15  15
080  54  )
081  95  =
082  42 STO
083  08  08
084  55  ÷
085  43 RCL
086  01  01
087  95  =
088  65  X
089  53  (
090  01  1
091  85  +
092  93  .
093  02  2
094  65  X
```

```
095  43  RCL
096  14   14
097  54   )
098  95   =
099  55   ÷
100  53   (
101  53   (
102  01   1
103  85   +
104  01   1
105  93   .
106  04   4
107  65   ×
108  43  RCL
109  14   14
110  54   )
111  33  X²
112  54   )
113  95   =
114  42  STO
115  16   16
116  53   (
117  01   1
118  75   -
119  04   4
120  93   .
121  08   8
122  65   ×
123  43  RCL
124  16   16
125  65   ×
126  43  RCL
127  14   14
128  54   )
129  95   =
130  32  X:T
131  00   0
132  22  INV
133  77   GE
134  12   B
135  61  GTO
136  00   00
137  49   49
138  91  R/S
139  68  NOP
140  68  NOP
141  76  LBL
142  12   B
```

```
143  32  X:T
144  34  ΓX
145  94  +/-
146  85   +
147  53   (
148  02   2
149  93   .
150  08   8
151  65   ×
152  43  RCL
153  14   14
154  65   ×
155  43  RCL
156  16   16
157  75   -
158  01   1
159  54   )
160  95   =
161  55   ÷
162  53   (
163  93   .
164  04   4
165  75   -
166  03   3
167  93   .
168  09   9
169  02   2
170  65   ×
171  43  RCL
172  14   14
173  65   ×
174  43  RCL
175  16   16
176  54   )
177  95   =
178  34  ΓX
179  32  X:T
180  01   1
181  22  INV
182  77   GE
183  15   E
184  61  GTO
185  00   00
186  49   49
187  91  R/S
188  76  LBL
189  15   E
190  32  X:T
```

```
191  68  NOP
192  33  X²
193  42  STO
194  17   17
195  61  GTO
196  03   03
197  78   78
198  43  RCL
199  08   08
200  99  PRT
201  43  RCL
202  02   02
203  33  X²
204  65   ×
205  93   .
206  02   2
207  85   +
208  01   1
209  95   =
210  42  STO
211  19   19
212  53   (
213  01   1
214  85   +
215  01   1
216  93   .
217  04   4
218  65   ×
219  43  RCL
220  14   14
221  54   )
222  55   ÷
223  53   (
224  01   1
225  85   +
226  01   1
227  93   .
228  04   4
229  65   ×
230  43  RCL
231  17   17
232  54   )
233  95   =
234  65   ×
235  53   (
236  53   (
237  53   (
238  01   1
```

```
239  85   +
240  93   .
241  02   2
242  65   ×
243  43  RCL
244  17   17
245  54   )
246  55   ÷
247  53   (
248  01   1
249  85   +
250  93   .
251  02   2
252  65   ×
253  43  RCL
254  14   14
255  54   )
256  54   )
257  45  YX
258  03   3
259  93   .
260  05   5
261  54   )
262  95   =
263  68  NOP
264  65   ×
265  43  RCL
266  13   13
267  65   ×
268  43  RCL
269  07   07
270  95   =
271  45  YX
272  93   .
273  02   2
274  08   8
275  06   6
276  95   =
277  68  NOP
278  42  STO
279  20   20
280  68  NOP
281  53   (
282  43  RCL
283  19   19
284  65   ×
285  43  RCL
286  20   20
```

| | | |
|---|---|---|
| 287 | 75 | - |
| 288 | 01 | 1 |
| 289 | 54 | ) |
| 290 | 65 | × |
| 291 | 53 | ( |
| 292 | 01 | 1 |
| 293 | 85 | + |
| 294 | 43 | RCL |
| 295 | 15 | 15 |
| 296 | 54 | ) |
| 297 | 65 | × |
| 298 | 53 | ( |
| 299 | 01 | 1 |
| 300 | 85 | + |
| 301 | 53 | ( |
| 302 | 43 | RCL |
| 303 | 15 | 15 |
| 304 | 65 | × |
| 305 | 43 | RCL |
| 306 | 09 | 09 |
| 307 | 65 | × |
| 308 | 43 | RCL |
| 309 | 03 | 03 |
| 310 | 54 | ) |
| 311 | 55 | ÷ |
| 312 | 53 | ( |
| 313 | 93 | . |
| 314 | 02 | 2 |
| 315 | 03 | 3 |
| 316 | 65 | × |
| 317 | 43 | RCL |
| 318 | 01 | 01 |
| 319 | 54 | ) |
| 320 | 54 | ) |
| 321 | 55 | ÷ |
| 322 | 53 | ( |
| 323 | 43 | RCL |
| 324 | 20 | 20 |
| 325 | 65 | × |
| 326 | 53 | ( |
| 327 | 43 | RCL |
| 328 | 19 | 19 |
| 329 | 75 | - |
| 330 | 01 | 1 |
| 331 | 54 | ) |
| 332 | 95 | = |
| 333 | 34 | √X |
| 334 | 75 | - |
| 335 | 01 | 1 |
| 336 | 95 | = |
| 337 | 65 | × |
| 338 | 43 | RCL |
| 339 | 04 | 04 |
| 340 | 65 | × |
| 341 | 43 | RCL |
| 342 | 06 | 06 |
| 343 | 65 | × |
| 344 | 43 | RCL |
| 345 | 05 | 05 |
| 346 | 33 | X² |
| 347 | 95 | = |
| 348 | 55 | ÷ |
| 349 | 03 | 3 |
| 350 | 02 | 2 |
| 351 | 93 | . |
| 352 | 01 | 1 |
| 353 | 07 | 7 |
| 354 | 95 | = |
| 355 | 99 | PRT |
| 356 | 61 | GTO |
| 357 | 10 | E' |
| 358 | 76 | LBL |
| 359 | 13 | C |
| 360 | 65 | × |
| 361 | 53 | ( |
| 362 | 43 | RCL |
| 363 | 02 | 02 |
| 364 | 33 | X² |
| 365 | 65 | × |
| 366 | 93 | . |
| 367 | 02 | 2 |
| 368 | 85 | + |
| 369 | 01 | 1 |
| 370 | 54 | ) |
| 371 | 95 | = |
| 372 | 99 | PRT |
| 373 | 42 | STO |
| 374 | 01 | 01 |
| 375 | 61 | GTO |
| 376 | 04 | 04 |
| 377 | 45 | 45 |
| 378 | 65 | × |
| 379 | 93 | . |
| 380 | 02 | 2 |
| 381 | 85 | + |
| 382 | 01 | 1 |

```
383  95   =
384  35  1/X
385  65   ×
386  43  RCL
387  08   08
388  95   =
389  32  X↕T
390  05   5
391  00   0
392  00   0
393  00   0
394  22  INV
395  77   GE
396  17  B'
397  32  X↕T
398  99  PRT
399  43  RCL
400  15   15
401  99  PRT
402  43  RCL
403  17   17
404  34  √X
405  99  PRT
406  61  GTO
407  01   01
408  98   98
409  91  R/S
410  76  LBL
411  19  D'
412  09   9
413  09   9
414  09   9
415  09   9
416  99  PRT
417  91  R/S
418  76  LBL
419  10  E'
420  98  ADV
421  43  RCL
422  27   27
423  42  STO
424  15   15
425  25  CLR
426  69  OP
427  22   22
428  43  RCL
429  02   02
430  16  A'
431  91  R/S
432  68  NOP
433  68  NOP
434  68  NOP
435  68  NOP
436  68  NOP
437  76  LBL
438  16  A'
439  99  PRT
440  42  STO
441  02   02
442  43  RCL
443  25   25
444  13   C
445  25  CLR
446  43  RCL
447  02   02
448  65   ×
449  43  RCL
450  26   26
451  95   =
452  42  STO
453  05   05
454  99  PRT
455  43  RCL
456  27   27
457  42  STO
458  15   15
459  11   A
460  91  R/S
461  81  RST
462  76  LBL
463  14   D
464  65   ×
465  43  RCL
466  08   08
467  95   =
468  32  X↕T
469  04   4
470  00   0
471  00   0
472  00   0
473  00   0
474  00   0
475  00   0
476  00   0
477  00   0
478  00   0
```

## APPENDIX B

## TI-59 SCRAMJET PROGRAM OUTPUT

Various scramjet parameters are presented for hypersonic flight at various altitudes from sea level to 150,000 feet.

| Altitude (feet) | $M_0$ | $T_{T0}$ (°R) | $V_0$ (ft/sec) | $T_5$ (°R) | f | $M_5$ | $T_{T5}$ (°R) | T (lbf) |
|---|---|---|---|---|---|---|---|---|
| 0 | 5 | 3112.13 | 5580 | 4051.94 | 0.0266 | 1.10 | 5024.32 | 17837.82 |
| | 6 | 4253.24 | 6696 | 4997.24 | 0.0376 | 1.38 | 6887.59 | 27256.33 |
| | 7 | 5601.83 | 7812 | 4976.24 | 0.0396 | 1.83 | 8319.59 | 29712.14 |
| | 8 | 7157.89 | 8928 | 4980.84 | 0.0411 | 2.23 | 9913.11 | 31697.62 |
| | 9 | 8921.43 | 10044 | 4992.14 | 0.0426 | 2.60 | 11701.04 | 33654.02 |
| 10,000 | 5 | 2898.16 | 5397 | 3761.02 | 0.0246 | 1.10 | 4676.10 | 12233.47 |
| | 6 | 3960.81 | 6476 | 4958.52 | 0.0371 | 1.28 | 6571.84 | 20070.64 |
| | 7 | 5216.68 | 7556 | 4953.15 | 0.0396 | 1.74 | 7949.12 | 22165.42 |
| | 8 | 6172.68 | 8298 | 4953.17 | 0.0411 | 2.13 | 9440.40 | 23605.33 |
| | 9 | 8308.05 | 9715 | 4967.43 | 0.0426 | 2.49 | 11112.72 | 25009.45 |
| 20,000 | 5 | 2684.21 | 5187 | 3466.42 | 0.0226 | 1.11 | 4325.52 | 8014.64 |
| | 6 | 3668.42 | 6224 | 4984.02 | 0.0366 | 1.13 | 6255.82 | 14223.52 |
| | 7 | 4831.57 | 7261 | 4992.22 | 0.0401 | 1.62 | 7612.03 | 16136.02 |
| | 8 | 6174.68 | 8299 | 4978.57 | 0.0416 | 2.01 | 9000.38 | 17150.71 |
| | 9 | 7694.73 | 9336 | 4991.95 | 0.0431 | 2.36 | 10556.30 | 18130.12 |
| | 10 | 9394.73 | 10373 | 4958.40 | 0.0441 | 2.71 | 12248.08 | 10044.38 |
| 30,000 | 5 | 2470.20 | 4973 | 3309.85 | 0.0211 | 1.03 | 4009.25 | 5235.26 |
| | 6 | 3375.94 | 5968 | 4743.11 | 0.0341 | 1.06 | 5802.09 | 9245.33 |
| | 7 | 4446.36 | 6963 | 4991.60 | 0.0401 | 1.50 | 7241.67 | 11322.25 |
| | 8 | 5681.46 | 7957 | 4959.58 | 0.0416 | 1.90 | 8527.83 | 12014.92 |
| | 9 | 7081.25 | 8952 | 4972.51 | 0.0431 | 2.24 | 9968.16 | 12677.54 |
| | 10 | 8645.71 | 9947 | 4989.23 | 0.0446 | 2.57 | 11562.01 | 13323.02 |

| Altitude (feet) | $M_0$ | $T_{T0}$ (°R) | $V_0$ (ft/sec) | $T_5$ (°R) | f | $M_5$ | $T_{T5}$ (°R) | T (lbf) |
|---|---|---|---|---|---|---|---|---|
| 40,000 | 5 | 2339.93 | 4843 | 3032.62 | 0.0196 | 1.11 | 3774.17 | 3177.28 |
| | 6 | 3197.90 | 5811 | 4473.08 | 0.0321 | 1.07 | 5491.71 | 5693.92 |
| | 7 | 4211.87 | 6780 | 4942.83 | 0.0396 | 1.44 | 6982.58 | 7345.04 |
| | 8 | 5381.83 | 7748 | 4951.35 | 0.0416 | 1.82 | 8240.16 | 7896.57 |
| | 9 | 6707.79 | 8717 | 4962.45 | 0.0431 | 2.16 | 9610.14 | 8323.30 |
| 50,000 | 5 | 2339.93 | 4840 | 3023.62 | 0.0196 | 1.11 | 3774.17 | 1958.56 |
| | 6 | 3197.90 | 5808 | 4473.08 | 0.0321 | 1.07 | 5491.71 | 3509.87 |
| | 7 | 4211.87 | 6777 | 4942.83 | 0.0396 | 1.44 | 6982.58 | 4527.66 |
| | 8 | 5381.83 | 7745 | 4951.35 | 0.0416 | 1.82 | 8240.16 | 4867.64 |
| | 9 | 6707.79 | 8713 | 4962.45 | 0.0431 | 2.16 | 9610.14 | 5130.69 |
| | 10 | 8189.75 | 9681 | 4981.58 | 0.0446 | 2.48 | 11125.52 | 5384.73 |
| 60,000 | 5 | 2339.93 | 4840 | 3032.62 | 0.0196 | 1.11 | 3774.17 | 1215.46 |
| | 6 | 3197.90 | 5808 | 4473.08 | 0.0321 | 1.07 | 5491.71 | 2178.20 |
| | 7 | 4211.87 | 6776 | 4942.83 | 0.0396 | 1.44 | 6982.58 | 2809.83 |
| | 8 | 5381.98 | 7744 | 4951.35 | 0.0416 | 1.82 | 8240.16 | 3020.81 |
| | 9 | 6707.79 | 8712 | 4962.45 | 0.0431 | 2.16 | 9610.14 | 3184.06 |
| 80,000 | 5 | 2339.93 | 4840 | 3032.62 | 0.0196 | 1.11 | 3774.17 | 464.24 |
| | 6 | 3197.90 | 5808 | 4473.08 | 0.0321 | 1.07 | 5491.71 | 831.95 |
| | 7 | 4211.87 | 6776 | 4942.83 | 0.0396 | 1.44 | 6982.58 | 1073.90 |
| | 8 | 5381,83 | 7744 | 4951.35 | 0.0416 | 1.82 | 8240.16 | 1153.78 |
| | 9 | 6707.79 | 8712 | 4962.45 | 0.0431 | 2.16 | 9610.14 | 1216.13 |
| 100,000 | 5 | 2517.48 | 5025 | 3247.16 | 0.0211 | 1.12 | 4055.55 | 182.82 |
| | 6 | 3440.56 | 6030 | 4775.08 | 0.0346 | 1.08 | 5898.92 | 328.61 |
| | 7 | 4531.46 | 7035 | 4990.11 | 0.0401 | 1.52 | 7323.49 | 396.20 |
| | 8 | 5790.20 | 8040 | 4963.27 | 0.0416 | 1.92 | 8632.22 | 420.59 |
| | 9 | 7216.78 | 9045 | 4976.52 | 0.0431 | 2.27 | 10098.09 | 443.96 |
| | 10 | 8811.18 | 10050 | 4992.24 | 0.0446 | 2.60 | 11720.42 | 466.80 |

| Altitude (feet) | $M_0$ | $T_{T0}$ (°R) | $V_0$ (ft/sec) | $T_5$ (°R) | f | $M_5$ | $T_{T5}$ (°R) | T (lbf) |
|---|---|---|---|---|---|---|---|---|
| 150,000 | 5 | 3011.26 | 5490 | 3902.20 | 0.0256 | 1.11 | 4856.84 | 24.72 |
| | 6 | 4115.38 | 6588 | 4941.18 | 0.0371 | 1.34 | 6720.88 | 38.81 |
| | 7 | 5420.26 | 7686 | 4964.63 | 0.0396 | 1.79 | 8144.94 | 42.91 |
| | 8 | 6925.89 | 8784 | 4967.47 | 0.0411 | 2.18 | 9690.26 | 45.74 |
| | 9 | 8632.27 | 9882 | 4980.29 | 0.0426 | 2.54 | 11423.69 | 48.52 |
| | 10 | 10539.40 | 10980 | 4984.97 | 0.0441 | 2.90 | 13344.40 | 51.31 |

## APPENDIX C
## GUN-LAUNCHED SCRAMJET/ROCKET ASAT MISSION PROFILE, PROGRAM LISTING

```
1 REM THIS PROGRAM WILL CALCULATE THE FLIGHT PATH FOR A 16", GUN-LAUNCHED ROCKET
2 REM OR SCRAMJET VEHICLE FOR USE IN AN ANTI-SATELLITE MISSION.  FLAT EARTH
3 REM TRAJECTORY IS ASSUMED.
4 REM FOR A SINGLE RUN WITH OUTPUT EVERY 10 SECONDS, ENTER RUN.
5 REM FOR A PROGRAM THAT WILL CALCULATE APOGEE FOR GUN ELEVATON ANGLES,(15-45)
6 REM DEG, ANGLE OF ATTACK,(0-12) DEG., AND POP-UP ALTITUDE,(100-11500) METERS,
7 REM RUN, DRAW THE AXISES THEN CONTINUE AT LINE 20.
8 REM-----------------------------------------------------------------------------
10 GOTO 200
15 REM --------------FOR  APOGEE RUN W8=0(SCRAMJET),W8=1(ROCKET).---------------
20 W8=0
30 W9=1
40 A7=-3
50 H1=0
60 A4=A=45
70 G9=0
80 H1=H1+100
90 PEN
100 IF H1>11500 THEN 2180
110 A7=A7+3
120 A=A4
130 IF A7<15 THEN 450
140 A7=3
150 A=A4=A4-5
160 IF A>10 THEN 450
170 A4=A=45
180 A7=0
190 GOTO 80
195 REM ------------AXIS SIZING---------------------------------------------------
200 X9=66666.667
210 Y9=66666.667
```

```
220 PRINT "HAVE THE AXES BEEN DRAWN?"
230 PRINT ""
240 DISP "YES=1,NO=0";
250 INPUT Z8
260 IF Z8=1 THEN 450
270 SCALE 0,3*X9,0,3*Y9
280 XAXIS 0,X9/10,0,3*X9
290 YAXIS 0,Y9/10,0,3*Y9
300 REM-------------INPUT ROUTINE-----------------------------------------------
310 DISP "INPUT GUN ELEVATION ANGLE,0-45 (DEG).";
320 WAIT 100
330 INPUT A
340 DISP "INPUT POP-UP ALT(M)";
350 WAIT 100
360 INPUT H1
370 DISP "INPUT ANGLE OF ATTACK (DEG).";
380 WAIT 100
390 INPUT A7
400 PRINT "ROCKET (INPUT(1)); SCRAMJET (INPUT(0))"
410 PRINT ":::::::::::::::::::::::::::::::::::::::::::::::::::::::::;"
420 INPUT W8
425 REM-------------PROGRAM INITIALIZATIION-------------------------------------
430 G9=10
440 W9=0
450 J=0
460 A3=10
470 R9=0.4572
480 L9=3
490 A8=80
500 M3=45
510 FORMAT 5F14.3
520 T=1
530 DEG
540 X8=1
550 X3=1
560 Y8=1
```

```
570 X1=X8
580 Y1=Y8
590 M7=0
600 M2=M=4.5
610 A2=360
620 V1=M2*A2
630 A9=0.1297
640 A0=0.0993
650 R0=0.3556
660 R7=1-(R0/R9)↑2
670 M1=325
680 M6=M1
690 G1=1.4
700 R=1.22642
710 H=7620
720 G=9.807
730 U=V1*COSA
740 V=V1*SINA
750 Q1=(1/2)*R*(V↑2+U↑2)*EXP(-Y1/H)
755 REM---------------INPUT ECHO------------------------------------------------------------
760 IF W8>0 THEN 2200
770 IF W9=1 THEN 850
780 DISP "WANT PRINT OF INPUT YES=1 NO=0";
790 INPUT W7
800 IF W7<1 THEN 850
810 PRINT "ELEVATION ANGLE=";A"POP-UP ALT=";H1
820 PRINT "ANGLE OF ATTACK=";A7"FUEL(KG)=";M3
830 PRINT "MAXF.P.ANGLE=";A8" DELTA TIME=";T
840 PRINT "INLET AREA(M↑2)=";A0
850 V8=V1*SINA
860 U8=V1*COSA
870 PLOT X1,Y1
880 X2=X3=X1+U*T
890 Y2=Y3=Y1+V*T
900 T1=T
910 PLOT X2,Y2
920 IF W9=1 THEN 1000
```

```
925 REM--------------OUTPUT FORMAT-----------------------------------------------------
930 PRINT "*****************************************************************"
940 PRINT "          ELAPSED          MACH          DRAG            ANGLE          THRUST"
950 PRINT "          TIME                                                                "
970 PRINT "-------------------------------------------------------------------------------"
980 PRINT "          LIFT        VELOCITY            MASS       DYN PRESS             ALT"
990 PRINT "******************************************************************"
1000 GOTO 1400
1010 Y3=(-G+(F*SIN(A+A7)+L*COSA-D*SINA)/M6)*(T↑2)+2*Y2-Y1
1020 X3=(F*COS(A+A7)-L*SINA-D*COSA)*(T↑2)/M6+2*X2-X1
1030 PLOT X3,Y3
1040 T1=T1+T
1050 IF W8>0 THEN 2350
1055 REM-------------SCRAMJET PAYLOAD SEPARATION-----------------------------------
1060 IF Y3<150000 THEN 1100
1070 M6=30
1080 GOTO 1130
1090 IF M3=0 THEN 1130
1095 REM----------------------------------------------------------------------------
1100 M7=M7+W
1110 M6=M1-M7
1120 M3=M3-W
1130 U=(X3-X2)/T
1140 V=(Y3-Y2)/T
1145 REM-------------APOGEE TEST-----------------------------------------------------
1150 IF (Y3-Y2)<0 THEN 2570
1155 REM-------------FLIGHT PATH ANGLE(A9), DYN.PRESS.(Q1), MACH #(M)-----------
1160 A=ATN((Y3-Y2)/(X3-X2))
1170 Q1=(1/2)*R*(V↑2+U↑2)*EXP(-Y3/H)
1180 M8=(U↑2+V↑2)/(A2↑2)
1190 M=SQR(M8)
```

```
1195 REM------------------------------------------------------------------------
1200 J=J+1
1210 IF W9=0 THEN 1240
1220 IF Y3>100000 THEN 1300
1230 GOTO 1360
1240 IF J=1 THEN 1300
1250 IF J=5 THEN 1300
1260 J1=INT(J/10)
1270 J2=(J/10)-J1
1280 IF J2=0 THEN 1300
1290 GOTO 1360
1300 V2=SQR(U↑2+V↑2)
1310 IF W9=1 THEN 1750
1320 WRITE (15,510)T1,M,D,A,F
1330 WRITE (15,510)L,V2,M6,Q1,Y3
1340 PRINT "****************************************************************"
1350 IF W9=1 THEN 90
1360 X1=X2
1370 Y1=Y2
1380 X2=X3
1390 Y2=Y3
1395 REM-----------IF VEHICLE IS ROCKET  CONT AT SONIC SPEED ROUTINE------------
1400 IF W8>0 THEN 1580
1405 REM------------IF MORE THAN 1 KG. OF FUEL CALL SCRAMJET THRUST ROUTINE-----
1410 IF M3>1 THEN 2600
1420 F=0
1490 IF Y3>10970 THEN 1550
1495 REM------------FUEL FLOW ROUTINE FOR SCRAMJET------------------------------
1500 IF M>6 THEN 1530
1510 F8=0.0226+0.011*(M-5)
1520 GOTO 1580
1530 F8=0.037+0.00177*(M-6)
1540 GOTO 1580
1550 IF M>7 THEN 1530
1560 F8=0.021+0.0093*(M-5)
1570 GOTO 1580
```

```
1575 REM-----------SPEED OF SOUND AS A FUNCTION OF ALT.(M/SEC)------------------
1580 IF Y3>11000 THEN 1620
1590 A2=360-0.006363*Y3
1600 IF W8>0 THEN 1740
1610 GOTO 1640
1620 A2=290
1630 IF W8>0 THEN 1890
1640 W0=A0*R*M*A2*EXP(-Y3/H)
1650 W=F8*W0
1660 GOTO 1890
1665 REM-----------SRCAMJET CONDTION POST FUEL EXHAUSTION-----------------------
1670 R9=0.3556
1680 A9=A0
1690 F=0
1700 W=0
1710 F8=0
1720 R0=0
1730 R7=1-(R0/R9)↑2
1740 GOTO 1890
1745 REM------------OUTPUT FOR APOGEE PROGRAM MODE-------------------------------
1750 Y5=Y3+(V↑2/(2*G))
1760 IF G9=1 THEN 1820
1770 PRINT "-------------------------------------------------------------"
1780 PRINT "TR.AL           M#              VEL(M/S)       G.EL  <AT   TALT"
1790 PRINT "MAX.ALT(M)---------------------------------------------------------"
1800 PRINT "--------------------------------------------------------------------"
1810 G9=1
1820 PRINT A;M;V2;A4;A7;H1;Y5
1830 PRINT "-------------------------------------------------------------------"
1840 GOTO 1350
1850 GOTO 1890
1860 IF W8=0 THEN 1890
1870 IF J9=0 THEN 1890
1880 A7=0
```

```
1885 REM----------HYPERSONIC AERODYNAMICS----------------------------------------
1890 IF Y3<H1 THEN 2070
1900 IF A>A8 THEN 2070
1910 IF A7>A3 THEN 1950
1920 L2=R7*(COSA)↑2*SIN(2*A7)
1930 L3=(R7*(2*(SINA3)↑2+(SINA7)↑2*(1-3*(SINA3)↑2)))
1940 GOTO 2020
1950 P8=0.01745*ATN(TANA3/(SQR((TANA7)↑2-(TANA3)↑2)))
1960 L2=(COSA3)↑2*SIN(2*A7)*((P8+1.57)/3.14)+0.0161*COS(P8*57.29578)
1970 L2=L2*((COSA7/SINA7)*TANA3+2*TANA7*(COSA3/SINA3))
1980 L2=L2*R7
1990 L3=((P8+1.57)/3.14)*(2*(SINA3)↑2+(SINA7)↑2*(1-3*(SINA3)↑2))
2000 L3=L3+0.2387*COS(P8*57.29578)*SIN(2*A7)*SIN(2*A3)
2010 L3=L3*R7
2020 L5=L2*SINA7+L3*COSA7
2030 L6=L2*COSA7-L3*SINA7
2040 L7=1.69765*(L9/R9)*(SINA7)↑2*COSA7
2050 L8=1.69765*(L9/R9)*(SINA7)↑2*SINA7
2060 GOTO 2090
2070 L5=R7*2*(SINA3)↑2
2080 L6=L7=L8=0
2090 C=L5+L8
2100 C6=L6+L7
2110 L=C6*A9*Q1
2120 GOTO 2430
2130 D=Q1*A9*C+D6
2140 C2=C
2170 GOTO 1010
```

```
2175 REM-----------ROCKET INITIALIZATION--------------------------------------
2200 A3=10.5
2210 R9=0.4191
2220 R0=0
2230 A0=0
2240 M1=345
2250 M2=M=4.5
2260 M3=216
2270 F=84556.5
2280 W=36
2290 J9=0
2300 L9=2.9432
2310 V1=M2*A2
2320 U=V1*COSA
2330 V=V1*SINA
2340 GOTO 770
2345 REM-----------ROCKET CONDITON POST FUEL EXHAUSTION-------------------------
2350 IF M3=0 THEN 2370
2360 GOTO 2400
2370 F=0
2380 W=0
2390 GOTO 2400
2395 REM ----------ROCKET PAYLOAD SEPARATION-----------------------------------
2400 IF Y3<150000 THEN 1090
2410 M6=30
2420 GOTO 1090
```

```
2425 REM------------SKIN FRICTION DRAG----------------------------------------------
2430 IF Y3>11000 THEN 2460
2440 U9=(Y3/-2.997E+09)+1.789E-05
2450 GOTO 2530
2460 IF Y3>25000 THEN 2490
2470 U9=1.422E-05
2480 GOTO 2530
2490 IF Y3>75000 THEN 2520
2500 U9=((Y3-25000)/-3.873E+09)+1.422E-05
2510 GOTO 2530
2520 U9=1.336E-06
2530 C7=1.328/SQR((EXP(-Y3/H)*(M*A2)*L9)/U9)
2540 D6=Q1*6.283*(R9/2)*L9*C7
2550 IF L=0 THEN 2560
2560 GOTO 2130
2565 REM------------APOGEE FAULT-----------------------------------------------------
2570 PRINT "FALLING OUT OF SKY";" ALT=";Y3"RNG=";X3"A="A
2580 PRINT "GUN.EL="A4,"ALFA="A7,"TALT="H1
2590 GOTO 90
2595 REM------------SCRAMJET THRUST -------------------------------------------------
2600 IF Y3>3048 THEN 2690
2610 IF M>6 THEN 2640
2620 F=(9500-Y3*0.5577)*(M-5)+17800-1.837*Y3
2630 GOTO 3100
2640 IF M>7 THEN 2670
2650 F=2133*(M-6)+27300-2.395*Y3
2660 GOTO 3100
2670 F=(2133-Y3*0.2241)*(M-7)+29700-2.49*Y3
2680 GOTO 3100
2690 IF Y3>6096 THEN 2780
2700 IF M>6 THEN 2730
2710 F=(7800-(Y3-3048)*0.5249)*(M-5)+12200-1.4*(Y3-3048)
2720 GOTO 3100
2730 IF M >= 7 THEN 2760
2740 F=(2100-(Y3-3048)*0.0656)*(M-6)+18800-1.9*(Y3-3804)
2750 GOTO 3100
2760 F=(1450-(Y3-3048)*0.1696)*(M-7)+21000-2.034*(Y3-3804)
2770 GOTO 3100
```

```
2780 IF Y3>9144 THEN 2870
2790 IF M>6 THEN 2820
2800 F=(6200-(Y3-6096)*0.72178)*(M-5)+8000-0.919*(Y3-6096)
2810 GOTO 3100
2820 IF M>7 THEN 2850
2830 F=(1900-(Y3-6096)*0.06562)*(M-6)+14200-1.64*(Y3-6096)
2840 GOTO 3100
2850 F=(933-(Y3-6096)*0.08737)*(M-7)+16100-1.57*(Y3-6096)
2860 GOTO 3100
2870 IF Y3>12192 THEN 2960
2880 IF M>6 THEN 2910
2890 F=(4000-(Y3-9144)*0.4921)*(M-5)+5200-0.656*(Y3-9144)
2900 GOTO 3100
2910 IF M >= 7 THEN 2940
2920 F=(2100-(Y3-9144)*0.164)*(M-6)+9900-1.4*(Y3-9144)
2930 GOTO 3100
2940 F=666.7*(M-7)+11300-1.31*(Y3-9144)
2950 GOTO 3100
2960 IF Y3>15240 THEN 3050
2970 IF M>6 THEN 3000
2980 F=(2500-(Y3-12192)*0.3281)*(M-5)+3200-0.3937*(Y3-12192)
2990 GOTO 3100
3000 IF M>7 THEN 3030
3010 F=(1600-(Y3-12192)*0.19685)*(M-6)+5700-0.72178*(Y3-12192)
3020 GOTO 3100
3030 F=(500-(Y3-12192)*0.0164)*(M-7)+7300-0.9186*(Y3-12192)
3040 GOTO 3100
3050 IF M>6 THEN 3080
3060 F=(17800+9500*(M-5))*EXP(-Y3/H)
3070 GOTO 3100
3080 F=(27300+2133*(M-6))*EXP(-Y3/H)
3090 GOTO 3100
3100 F=4.45*F*(A0/0.111)
3110 GOTO 1490
3120 STOP
```

## APPENDIX D

### GUN-LAUNCHED SCRAMJET ASAT APOGEE AS A FUNCTION OF GUN ELEVATION, ANGLE OF ATTACK AND POP-UP ALTITUDE

| Gun Elevation (DEG) | Angle of Attack (DEG) | Pop-up Altitude (m) | Apogee (Km) |
|---|---|---|---|
| 30 | 0 | 0 | 123 |
| 35 | 0 | 0 | 169 |
| 40 | 0 | 0 | 214 |
| 45 | 0 | 0 | 239 |
| 15 | 3 | 500 | 162 |
| 20 | 3 | 500 | 186 |
| 25 | 3 | 500 | 209 |
| 30 | 3 | 500 | 236 |
| 35 | 3 | 500 | 265 |
| 40 | 3 | 500 | 275 |
| 45 | 3 | 500 | 286 |
| 15 | 3 | 1000 | 161 |
| 20 | 3 | 1000 | 165 |
| 25 | 3 | 1000 | 208 |
| 30 | 3 | 1000 | 228 |
| 35 | 3 | 1000 | 258 |
| 40 | 3 | 1000 | 275 |
| 45 | 3 | 1000 | 302 |
| 15 | 3 | 1500 | 135 |
| 20 | 3 | 1500 | 162 |
| 25 | 3 | 1500 | 188 |
| 30 | 3 | 1500 | 228 |
| 35 | 3 | 1500 | 258 |
| 40 | 3 | 1500 | 272 |
| 45 | 3 | 1500 | 282 |
| 15 | 3 | 3000 | 127 |
| 20 | 3 | 3000 | 155 |
| 25 | 3 | 3000 | 184 |
| 30 | 3 | 3000 | 219 |
| 35 | 3 | 3000 | 249 |
| 40 | 3 | 3000 | 270 |
| 45 | 3 | 3000 | 280 |

| Gun Elevation (DEG) | Angle of Attack (DEG) | Pop-up Altitude (m) | Apogee (Km) |
| --- | --- | --- | --- |
| 25 | 3 | 6000 | 168 |
| 30 | 3 | 6000 | 197 |
| 35 | 3 | 6000 | 233 |
| 40 | 3 | 6000 | 265 |
| 45 | 3 | 6000 | 274 |
| 20 | 3 | 9000 | 114 |
| 25 | 3 | 9000 | 157 |
| 30 | 3 | 9000 | 183 |
| 35 | 3 | 9000 | 223 |
| 40 | 3 | 9000 | 257 |
| 45 | 3 | 9000 | 269 |
| 25 | 3 | 11000 | 142 |
| 30 | 3 | 11000 | 178 |
| 35 | 3 | 11000 | 219 |
| 40 | 3 | 11000 | 254 |
| 45 | 3 | 11000 | 267 |
| 15 | 6 | 500 | 305 |
| 20 | 6 | 500 | 329 |
| 25 | 6 | 500 | 343 |
| 30 | 6 | 500 | 334 |
| 35 | 6 | 500 | 330 |
| 40 | 6 | 500 | 328 |
| 45 | 6 | 500 | 329 |
| 15 | 6 | 1000 | 227 |
| 20 | 6 | 1000 | 314 |
| 25 | 6 | 1000 | 330 |
| 30 | 6 | 1000 | 337 |
| 35 | 6 | 1000 | 332 |
| 40 | 6 | 1000 | 328 |
| 45 | 6 | 1000 | 329 |
| 15 | 6 | 1500 | 276 |
| 20 | 6 | 1500 | 294 |
| 25 | 6 | 1500 | 318 |
| 30 | 6 | 1500 | 337 |
| 35 | 6 | 1500 | 332 |
| 40 | 6 | 1500 | 329 |
| 45 | 6 | 1500 | 326 |

| Gun Elevation (DEG) | Angle of Attack (DEG) | Pop-up Altitude (m) | Apogee (Km) |
|---|---|---|---|
| 15 | 6 | 3000 | 269 |
| 20 | 6 | 3000 | 256 |
| 25 | 6 | 3000 | 302 |
| 30 | 6 | 3000 | 321 |
| 35 | 6 | 3000 | 331 |
| 40 | 6 | 3000 | 327 |
| 45 | 6 | 3000 | 326 |
| 15 | 6 | 6000 | 188 |
| 20 | 6 | 6000 | 228 |
| 25 | 6 | 6000 | 253 |
| 30 | 6 | 6000 | 287 |
| 35 | 6 | 6000 | 308 |
| 40 | 6 | 6000 | 317 |
| 45 | 6 | 6000 | 316 |
| 15 | 6 | 9000 | 133 |
| 20 | 6 | 9000 | 196 |
| 25 | 6 | 9000 | 229 |
| 30 | 6 | 9000 | 321 |
| 35 | 6 | 9000 | 283 |
| 40 | 6 | 9000 | 300 |
| 45 | 6 | 9000 | 303 |
| 15 | 6 | 11000 | 115 |
| 20 | 6 | 11000 | 164 |
| 25 | 6 | 11000 | 201 |
| 30 | 6 | 11000 | 245 |
| 35 | 6 | 11000 | 272 |
| 40 | 6 | 11000 | 293 |
| 45 | 6 | 11000 | 297 |
| 15 | 9 | 500 | 409 |
| 20 | 9 | 500 | 380 |
| 25 | 9 | 500 | 368 |
| 30 | 9 | 500 | 355 |
| 35 | 9 | 500 | 345 |
| 40 | 9 | 500 | 341 |
| 45 | 9 | 500 | 333 |

| Gun Elevation (DEG) | Angle of Attack (DEG) | Pop-up Altitude (m) | Apogee (Km) |
|---|---|---|---|
| 15 | 9 | 1000 | 403 |
| 20 | 9 | 1000 | 405 |
| 25 | 9 | 1000 | 387 |
| 30 | 9 | 1000 | 374 |
| 35 | 9 | 1000 | 362 |
| 40 | 9 | 1000 | 360 |
| 45 | 9 | 1000 | 333 |
| 15 | 9 | 1500 | 345 |
| 20 | 9 | 1500 | 404 |
| 25 | 9 | 1500 | 403 |
| 30 | 9 | 1500 | 374 |
| 35 | 9 | 1500 | 360 |
| 40 | 9 | 1500 | 350 |
| 45 | 9 | 1500 | 344 |
| 15 | 9 | 3000 | 341 |
| 20 | 9 | 3000 | 360 |
| 25 | 9 | 3000 | 389 |
| 30 | 9 | 3000 | 389 |
| 35 | 9 | 3000 | 370 |
| 40 | 9 | 3000 | 358 |
| 45 | 9 | 3000 | 348 |
| 15 | 9 | 6000 | 304 |
| 20 | 9 | 6000 | 288 |
| 25 | 9 | 6000 | 342 |
| 30 | 9 | 6000 | 368 |
| 35 | 9 | 6000 | 361 |
| 40 | 9 | 6000 | 358 |
| 45 | 9 | 6000 | 349 |
| 15 | 9 | 9000 | 249 |
| 20 | 9 | 9000 | 249 |
| 25 | 9 | 9000 | 285 |
| 30 | 9 | 9000 | 321 |
| 35 | 9 | 9000 | 339 |
| 40 | 9 | 9000 | 341 |
| 45 | 9 | 9000 | 332 |

| Gun Elevation (DEG) | Angle of Attack (DEG) | Pop-up Altitude (m) | Apogee (Km) |
|---|---|---|---|
| 15 | 9 | 11000 | 209 |
| 20 | 9 | 11000 | 210 |
| 25 | 9 | 11000 | 269 |
| 30 | 9 | 11000 | 308 |
| 35 | 9 | 11000 | 321 |
| 40 | 9 | 11000 | 330 |
| 45 | 9 | 11000 | 325 |
| 15 | 12 | 500 | 414 |
| 20 | 12 | 500 | 360 |
| 25 | 12 | 500 | 317 |
| 30 | 12 | 500 | 346 |
| 35 | 12 | 500 | 339 |
| 40 | 12 | 500 | 293 |
| 45 | 12 | 500 | 335 |
| 15 | 12 | 1000 | 463 |
| 20 | 12 | 1000 | 398 |
| 25 | 12 | 1000 | 379 |
| 30 | 12 | 1000 | 349 |
| 35 | 12 | 1000 | 361 |
| 40 | 12 | 1000 | 293 |
| 45 | 12 | 1000 | 335 |
| 15 | 12 | 1500 | 478 |
| 20 | 12 | 1500 | 479 |
| 25 | 12 | 1500 | 408 |
| 30 | 12 | 1500 | 349 |
| 35 | 12 | 1500 | 361 |
| 40 | 12 | 1500 | 352 |
| 45 | 12 | 1500 | 337 |
| 15 | 12 | 3000 | 509 |
| 20 | 12 | 3000 | 465 |
| 25 | 12 | 3000 | 439 |
| 30 | 12 | 3000 | 411 |
| 35 | 12 | 3000 | 372 |
| 40 | 12 | 3000 | 365 |
| 45 | 12 | 3000 | 355 |

| Gun Elevation (DEG) | Angle of Attack (DEG) | Pop-up Altitude (m) | Apogee (Km) |
|---|---|---|---|
| 15 | 12 | 6000 | 558 |
| 20 | 12 | 6000 | 445 |
| 25 | 12 | 6000 | 426 |
| 30 | 12 | 6000 | 405 |
| 35 | 12 | 6000 | 402 |
| 40 | 12 | 6000 | 375 |
| 45 | 12 | 6000 | 361 |
| 15 | 12 | 9000 | 392 |
| 20 | 12 | 9000 | 442 |
| 25 | 12 | 9000 | 416 |
| 30 | 12 | 9000 | 419 |
| 35 | 12 | 9000 | 405 |
| 40 | 12 | 9000 | 379 |
| 45 | 12 | 9000 | 360 |
| 15 | 12 | 11000 | 332 |
| 20 | 12 | 11000 | 401 |
| 25 | 12 | 11000 | 411 |
| 30 | 12 | 11000 | 406 |
| 35 | 12 | 11000 | 397 |
| 40 | 12 | 11000 | 377 |
| 45 | 12 | 11000 | 360 |

# APPENDIX E

## MAXIMUM APOGEE TRAJECTORY, LISTINGS

Units:

Time = Seconds
Velocity = Meters/Second
Lift
Drag Newtons
Thrust
Mass = KG
Altitude = Meters
Dynamic Pressure = Newton/Meter$^2$
Angle = Degrees

## I. SCRAMJET

```
ELEVATION ANGLE= 15   POP-UP ALT= 6000
ANGLE OF ATTACK= 12   FUEL(KG)= 45
MAXF.P.ANGLE= 80    DELTA TIME= 1
INLET AREA(M↑2)= 0.0993
****************************************************************
****************************************************************
        ELAPSED        MACH         DRAG          ANGLE         THRUST
        TIME
-------------------------------------------------------------------
        LIFT        VELOCITY          MASS       DYN PRESS          ALT
*******************************************************************
         2.000          4.895      5546.445         15.724     49344.343
         0.000       1749.046       321.831    1668181.437       894.279
****************************************************************
```

| | | | | |
|---|---|---|---|---|
| 6.000 | 7.683 | 8136.645 | 19.990 | 88628.609 |
| 0.000 | 2626.330 | 297.923 | 2585927.279 | 3749.368 |
| 11.000 | 10.158 | 102462.196 | 79.829 | 0.000 |
| 362367.489 | 3272.111 | 275.249 | 1149956.524 | 13274.794 |
| 21.000 | 9.881 | 261.729 | 86.065 | 0.000 |
| 0.000 | 3183.084 | 275.249 | 15943.447 | 45456.046 |
| 31.000 | 9.571 | 6.548 | 85.940 | 0.000 |
| 0.000 | 3083.169 | 275.249 | 249.275 | 76655.847 |
| 41.000 | 9.267 | 0.472 | 85.806 | 0.000 |
| 0.000 | 2985.287 | 275.249 | 4.432 | 106870.276 |
| 51.000 | 8.964 | 0.059 | 85.664 | 0.000 |
| 0.000 | 2887.482 | 275.249 | 0.089 | 136103.791 |
| 61.000 | 8.660 | 0.009 | 85.512 | 0.000 |
| 0.000 | 2789.700 | 30.000 | 0.002 | 164356.574 |
| 71.000 | 8.357 | 0.001 | 85.348 | 0.000 |
| 0.000 | 2691.941 | 30.000 | 0.000 | 191628.634 |
| 81.000 | 8.053 | 0.000 | 85.173 | 0.000 |
| 0.000 | 2594.206 | 30.000 | 0.000 | 217919.990 |
| 91.000 | 7.750 | 0.000 | 84.983 | 0.000 |
| 0.000 | 2496.497 | 30.000 | 0.000 | 243230.644 |
| 101.000 | 7.447 | 0.000 | 84.779 | 0.000 |
| 0.000 | 2398.818 | 30.000 | 0.000 | 267560.598 |
| 111.000 | 7.144 | 0.000 | 84.556 | 0.000 |
| 0.000 | 2301.172 | 30.000 | 0.000 | 290909.853 |
| 121.000 | 6.841 | 0.000 | 84.314 | 0.000 |
| 0.000 | 2203.564 | 30.000 | 0.000 | 313278.407 |

| | | | | |
|---|---|---|---|---|
| 131.000 | 6.538 | 0.000 | 84.050 | 0.000 |
| 0.000 | 2105.999 | 30.000 | 0.000 | 334666.261 |
| 141.000 | 6.235 | 0.000 | 83.760 | 0.000 |
| 0.000 | 2008.483 | 30.000 | 0.000 | 355073.415 |
| 151.000 | 5.932 | 0.000 | 83.440 | 0.000 |
| 0.000 | 1911.024 | 30.000 | 0.000 | 374499.870 |
| 161.000 | 5.630 | 0.000 | 83.087 | 0.000 |
| 0.000 | 1813.631 | 30.000 | 0.000 | 392945.624 |
| 171.000 | 5.328 | 0.000 | 82.692 | 0.000 |
| 0.000 | 1716.314 | 30.000 | 0.000 | 410410.678 |
| 181.000 | 5.026 | 0.000 | 82.251 | 0.000 |
| 0.000 | 1619.089 | 30.000 | 0.000 | 426895.032 |
| 191.000 | 4.725 | 0.000 | 81.753 | 0.000 |
| 0.000 | 1521.972 | 30.000 | 0.000 | 442398.687 |
| 201.000 | 4.424 | 0.000 | 81.188 | 0.000 |
| 0.000 | 1424.985 | 30.000 | 0.000 | 456921.641 |
| 211.000 | 4.123 | 0.000 | 80.540 | 0.000 |
| 0.000 | 1328.158 | 30.000 | 0.000 | 470463.895 |
| 221.000 | 3.823 | 0.000 | 79.790 | 0.000 |
| 0.000 | 1231.527 | 30.000 | 0.000 | 483025.449 |
| 231.000 | 3.524 | 0.000 | 78.912 | 0.000 |
| 0.000 | 1135.144 | 30.000 | 0.000 | 494606.304 |

| | | | | |
|---|---|---|---|---|
| 241.000 | 3.226 | 0.000 | 77.872 | 0.000 |
| 0.000 | 1039.075 | 30.000 | 0.000 | 505206.458 |
| 251.000 | 2.929 | 0.000 | 76.621 | 0.000 |
| 0.000 | 943.419 | 30.000 | 0.000 | 514825.912 |
| 261.000 | 2.633 | 0.000 | 75.088 | 0.000 |
| 0.000 | 848.315 | 30.000 | 0.000 | 523464.667 |
| 271.000 | 2.341 | 0.000 | 73.169 | 0.000 |
| 0.000 | 753.970 | 30.000 | 0.000 | 531122.721 |
| 281.000 | 2.051 | 0.000 | 70.706 | 0.000 |
| 0.000 | 660.711 | 30.000 | 0.000 | 537800.075 |
| 291.000 | 1.767 | 0.000 | 67.442 | 0.000 |
| 0.000 | 569.072 | 30.000 | 0.000 | 543496.730 |
| 301.000 | 1.490 | 0.000 | 62.947 | 0.000 |
| 0.000 | 479.982 | 30.000 | 0.000 | 548212.684 |
| 311.000 | 1.227 | 0.000 | 56.466 | 0.000 |
| 0.000 | 395.168 | 30.000 | 0.000 | 551947.938 |
| 321.000 | 0.987 | 0.000 | 46.658 | 0.000 |
| 0.000 | 318.070 | 30.000 | 0.000 | 554702.492 |
| 331.000 | 0.794 | 0.000 | 31.400 | 0.000 |
| 0.000 | 255.762 | 30.000 | 0.000 | 556476.347 |
| 341.000 | 0.686 | 0.000 | 9.156 | 0.000 |
| 0.000 | 221.123 | 30.000 | 0.000 | 557269.501 |
| 351.000 | 0.705 | 0.000 | -16.070 | 0.000 |
| 0.000 | 227.183 | 30.000 | 0.000 | 557081.955 |

```
^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
      361.000        0.842        0.000      -36.401        0.000
        0.000      271.228       30.000        0.000   555913.710
**************************************************************
      371.000        1.052        0.000      -49.876        0.000
        0.000      338.751       30.000        0.000   553764.764
**************************************************************
      381.000        1.299        0.000      -58.561        0.000
        0.000      418.539       30.000        0.000   550635.118
**************************************************************
      391.000        1.567        0.000      -64.377        0.000
        0.000      504.811       30.000        0.000   546524.773
**************************************************************
      401.000        1.846        0.000      -68.466        0.000
        0.000      594.750       30.000        0.000   541433.727
**************************************************************
      411.000        2.132        0.000      -71.470        0.000
        0.000      686.919       30.000        0.000   535361.981
**************************************************************
      421.000        2.423        0.000      -73.758        0.000
        0.000      780.527       30.000        0.000   528309.535
**************************************************************
      431.000        2.717        0.000      -75.554        0.000
        0.000      875.113       30.000        0.000   520276.390
**************************************************************
```

II. ROCKET

ELEVATION ANGLE= 45   POP-UP ALT= 100
ANGLE OF ATTACK= 12   FUEL(KG)= 216
MAXF.P.ANGLE= 80   DELTA TIME= 1
INLET AREA(M↑2)= 0

| ELAPSED TIME | MACH | DRAG | ANGLE | THRUST |
|---|---|---|---|---|
| LIFT | VELOCITY | MASS | DYN PRESS | ALT |
| 2.000 | 5.179 | 49689.673 | 65.178 | 84556.500 |
| 189467.605 | 1826.784 | 309.000 | 1416255.808 | 2804.536 |
| 6.000 | 10.090 | 4532.344 | 86.939 | 84556.500 |
| 0.000 | 3007.758 | 165.000 | 1043213.958 | 12733.293 |
| 11.000 | 14.661 | 1155.192 | 81.846 | 0.000 |
| 0.000 | 4251.735 | 129.000 | 146255.136 | 32979.430 |
| 21.000 | 14.277 | 11.276 | 81.654 | 0.000 |
| 0.000 | 4140.308 | 129.000 | 603.747 | 74408.147 |
| 31.000 | 13.942 | 0.397 | 81.452 | 0.000 |
| 0.000 | 4043.131 | 129.000 | 2.860 | 114832.022 |
| 41.000 | 13.607 | 0.028 | 81.240 | 0.000 |
| 0.000 | 3946.168 | 30.000 | 0.015 | 154274.751 |
| 51.000 | 13.273 | 0.002 | 81.018 | 0.000 |
| 0.000 | 3849.268 | 30.000 | 0.000 | 192736.731 |
| 61.000 | 12.939 | 0.000 | 80.784 | 0.000 |
| 0.000 | 3752.431 | 30.000 | 0.000 | 230218.001 |
| 71.000 | 12.606 | 0.000 | 80.538 | 0.000 |
| 0.000 | 3655.661 | 30.000 | 0.000 | 266718.571 |

| | | | | |
|---|---|---|---|---|
| 81.000 | 12.272 | 0.000 | 80.279 | 0.000 |
| 0.000 | 3558.961 | 30.000 | 0.000 | 302238.440 |
| 91.000 | 11.939 | 0.000 | 80.004 | 0.000 |
| 0.000 | 3462.339 | 30.000 | 0.000 | 336777.610 |
| 101.000 | 11.606 | 0.000 | 79.715 | 0.000 |
| 0.000 | 3365.801 | 30.000 | 0.000 | 370336.079 |
| 111.000 | 11.274 | 0.000 | 79.408 | 0.000 |
| 0.000 | 3269.354 | 30.000 | 0.000 | 402913.849 |
| 121.000 | 10.941 | 0.000 | 79.082 | 0.000 |
| 0.000 | 3173.006 | 30.000 | 0.000 | 434510.919 |
| 131.000 | 10.610 | 0.000 | 78.736 | 0.000 |
| 0.000 | 3076.767 | 30.000 | 0.000 | 465127.288 |
| 141.000 | 10.278 | 0.000 | 78.368 | 0.000 |
| 0.000 | 2980.648 | 30.000 | 0.000 | 494762.958 |
| 151.000 | 9.947 | 0.000 | 77.975 | 0.000 |
| 0.000 | 2884.659 | 30.000 | 0.000 | 523417.928 |
| 161.000 | 9.617 | 0.000 | 77.556 | 0.000 |
| 0.000 | 2788.816 | 30.000 | 0.000 | 551092.197 |
| 171.000 | 9.287 | 0.000 | 77.106 | 0.000 |
| 0.000 | 2693.133 | 30.000 | 0.000 | 577785.767 |
| 181.000 | 8.957 | 0.000 | 76.623 | 0.000 |
| 0.000 | 2597.628 | 30.000 | 0.000 | 603498.637 |
| 191.000 | 8.629 | 0.000 | 76.104 | 0.000 |
| 0.000 | 2502.322 | 30.000 | 0.000 | 628230.806 |

| | | | | |
|---|---|---|---|---|
| 201.000 | 8.301 | 0.000 | 75.543 | 0.000 |
| 0.000 | 2407.237 | 30.000 | 0.000 | 651982.276 |
| 211.000 | 7.974 | 0.000 | 74.937 | 0.000 |
| 0.000 | 2312.402 | 30.000 | 0.000 | 674753.046 |
| 221.000 | 7.648 | 0.000 | 74.278 | 0.000 |
| 0.000 | 2217.848 | 30.000 | 0.000 | 696543.115 |
| 231.000 | 7.323 | 0.000 | 73.561 | 0.000 |
| 0.000 | 2123.613 | 30.000 | 0.000 | 717352.485 |
| 241.000 | 6.999 | 0.000 | 72.778 | 0.000 |
| 0.000 | 2029.742 | 30.000 | 0.000 | 737181.155 |
| 251.000 | 6.677 | 0.000 | 71.919 | 0.000 |
| 0.000 | 1936.287 | 30.000 | 0.000 | 756029.125 |
| 261.000 | 6.356 | 0.000 | 70.972 | 0.000 |
| 0.000 | 1843.311 | 30.000 | 0.000 | 773896.394 |
| 271.000 | 6.038 | 0.000 | 69.926 | 0.000 |
| 0.000 | 1750.891 | 30.000 | 0.000 | 790782.964 |
| 281.000 | 5.721 | 0.000 | 68.764 | 0.000 |
| 0.000 | 1659.121 | 30.000 | 0.000 | 806688.834 |
| 291.000 | 5.407 | 0.000 | 67.465 | 0.000 |
| 0.000 | 1568.113 | 30.000 | 0.000 | 821614.003 |
| 301.000 | 5.097 | 0.000 | 66.008 | 0.000 |
| 0.000 | 1478.008 | 30.000 | 0.000 | 835558.473 |
| 311.000 | 4.790 | 0.000 | 64.363 | 0.000 |
| 0.000 | 1388.984 | 30.000 | 0.000 | 848522.243 |

| | | | | |
|---|---|---|---|---|
| 321.000 | 4.487 | 0.000 | 62.495 | 0.000 |
| 0.000 | 1301.260 | 30.000 | 0.000 | 860505.312 |
| 331.000 | 4.190 | 0.000 | 60.359 | 0.000 |
| 0.000 | 1215.120 | 30.000 | 0.000 | 871507.682 |
| 341.000 | 3.900 | 0.000 | 57.900 | 0.000 |
| 0.000 | 1130.924 | 30.000 | 0.000 | 881529.352 |
| 351.000 | 3.618 | 0.000 | 55.053 | 0.000 |
| 0.000 | 1049.141 | 30.000 | 0.000 | 890570.322 |
| 361.000 | 3.346 | 0.000 | 51.735 | 0.000 |
| 0.000 | 970.382 | 30.000 | 0.000 | 898630.591 |
| 371.000 | 3.088 | 0.000 | 47.845 | 0.000 |
| 0.000 | 895.445 | 30.000 | 0.000 | 905710.161 |
| 381.000 | 2.846 | 0.000 | 43.272 | 0.000 |
| 0.000 | 825.370 | 30.000 | 0.000 | 911809.031 |
| 391.000 | 2.626 | 0.000 | 37.891 | 0.000 |
| 0.000 | 761.503 | 30.000 | 0.000 | 916927.200 |
| 401.000 | 2.433 | 0.000 | 31.593 | 0.000 |
| 0.000 | 705.530 | 30.000 | 0.000 | 921064.670 |
| 411.000 | 2.274 | 0.000 | 24.316 | 0.000 |
| 0.000 | 659.465 | 30.000 | 0.000 | 924221.440 |
| 421.000 | 2.157 | 0.000 | 16.101 | 0.000 |
| 0.000 | 625.500 | 30.000 | 0.000 | 926397.509 |
| 431.000 | 2.089 | 0.000 | 7.152 | 0.000 |
| 0.000 | 605.675 | 30.000 | 0.000 | 927592.879 |

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